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LEVEL

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EC/2107301-FR

FINAL REPORT

DESIGN AND FEASIBILITY STUDY OF AN
OFF-LINE DIGITAL ORTHOPRINTER
FOR FIELD USE

EIKONIX Corporation
103 Terrace Hall Avenue
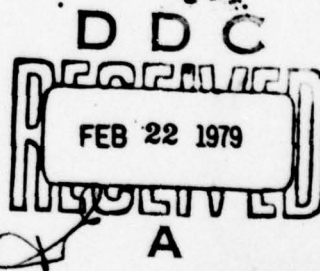Burlington, Massachusetts 01803

September 11, 1978

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Approved for Public Release; Distribution Unlimited

Prepared for:
U.S. Army Engineery Topographic Laboratories
Fort Belvoir, Virginia 22060

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A van-mounted off-line orthoprinter suitable for field use is required. A digital orthoprinter provides a simpler and more rugged system design compared to the complex and sensitive hardware systems commercially available. This program was performed to evaluate the feasibility of an off-line digital orthoprinter that provides the required ruggedness and the speed and accuracy for orthophotos. In pursuance of this program EIKONIX formulated a system concept that employs a drum scanner writer for the van-mounted digital orthoprinter. Available rectification and differential rectification

20. Continued

algorithms were implemented during this program to evaluate distortion parameters expected from camera systems. These distortion parameters were required inputs for design of the drum scanner with a solid state linear array. This work demonstrates that the digital, drum scanner design approach meets the objectives for orthophoto production in the field.

EIKONIX

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PREFACE

This document describes a study program on the design and feasibility for a van-mounted, off-line digital orthoprinter suitable for field use. This program was performed under Contract DAAK70-77-C-0196 by EIKONIX Corporation, 103 Terrace Hall Avenue, Burlington, Massachusetts for the U.S. Army Engineering Topographic Laboratories (USAETL), Ft. Belvoir, Virginia. The work described herein was conducted between 30 August 1977 and 30 April 1978. Mr. Maurits Roos was the USAETL Contracting Officer's Technical Representative.

1 INTRODUCTION

The production of planimetrically corrected photographic images (orthophotos and rectified photos) is a complex analytical process that is performed by optomechanical and digital instrumentation. The process is one of redistribution of elementary photo areas to correct the input imagery for distortions. The analytical description of the processes is quite complex, but has also been very well developed over recent years. To this end this study considered the design and feasibility of the system, not the analytical developments.

Orthophoto production has typically been performed in permanent facilities, ideally suited to maintain a stable environment for complex and sensitive hardware. The goal of this program is to perform a feasibility study for a field hardened van-mounted digital orthoprinter. To this end we have evaluated existing orthophoto instrumentation. It is found that no commercially available orthophoto production systems satisfy the field hardened requirements. We therefore have conceptually designed a digital orthophoto system that can withstand the environmental factors of field transportation off paved roads, and operation with non-ideal personnel.

This final report provides a survey and evaluation of available orthophoto equipment. It also describes a design approach for an off-line digital orthophoto production system that can withstand field environments, and a basically simple electro-optical design. The film scanner is a hardened drum scanner combined with a solid state linear photo-diode array. This simplifies what is typically the most complex and sensitive portion of any optomechanical scanning config-uration. Software procedures simplify initialization and operation of the processes. The orthophoto printer is also a drum scanner system. The basic concepts of the digital orthophoto system are developed in this work to a level where a design study can produce system specifications for production of a prototype unit.

2 OBJECTIVES AND RESULTS

The objective of this program, simply stated, was to study the design and feasibility of an off-line digital orthophoto system for field use. This section presents a listing of the items studied in this program (2.1) and a statement of the results of this effort (2.2).

2.1 Program Objectives

A summary of the program for Design and Feasibility Study of an Off-Line Digital Orthoprinter for Field Use is presented here. The program can be described by the following six tasks:

1. A review and documentation of the existing significant commercial orthoproduction techniques and their performances was conducted. This is reported in Section 3.3 and Appendix A.

2. A set of criteria for evaluation of a field hardened orthoprinter was developed. This is reported in Section 3.5.

3. From a study of various rectification algorithms, performed from the point of view of photogrammetric accuracy and processing complexity, an algorithm for orthophoto production was selected and is described in Section 3.2 together with the system model.

4. An empirical study of the rectification procedure was performed. Parameters in the rectification process were evaluated using model imagery and graphics analysis. This work is reported in Section 3.4

5. System parameters in scanning array size and spot shape and size are evaluated. This is discussed in Sections 3.4.1 and 4.3 and in Appendix B.

6. A conceptual design of a prototype off-line digital ortho-
    printer has been performed. The design is described in
    Section 4.1. This approach serves as a base for perform-
    ance of a design study that is recommended to generate
    final design specifications for the field hardened unit.

2.2   Program Results

The result of this program can be concisely stated in that the
objective for determination of the feasibility of the van-mounted digital ortho-
printer was met. The prime specifications that are met by the recom-
mended linear array detector and drum scanner configuration are production
of the orthophoto at a 3 square inch per minute rate, image sampling period
of $50\,\mu$ m and a design approach that is stable and simple for field use. A digital
control system has the advantage of minimum operating complexity. It "leads"
an operator through the set-up and the initializing tasks that will vary with
different camera products (e.g. panoramic, frame, strip, etc.). Operator
interaction with the system can be through a function board that minimizes
complex language for system communication. Display prompts will define
hardware set-up procedures as well as system procedures. The approach
generated by this study design is a good base to define system
elements and to generate specific hardware/software specifications.

3 ANALYTICAL REVIEW AND EVALUATION

3.1 Statement of Approach

Photogrammetry is a field that has received strong emphasis over the past two decades. The understanding of the physical processes of rectification and differential rectification is well developed. The approach taken for this program is not to pursue algorithm development but to develop a design approach of a simple digital orthophoto system.

A digital off-line orthophoto system provides distinct advantages for a field hardened system. A basic advantage of the digital system lies in the fact that a complex opto-mechanical rectifier can be avoided. Image data scanning can be performed with a compact and stable scanner-digitizer, rectification can be performed via software, and a printer can be built on the same principle as the scanner. EIKONIX has been studying hardware and software aspects of the off-line digital orthoprinter, and has concluded that such a system is not only practical but is highly recommended for field use.

This chapter presents a description of the rectification model used in this program to assess software requirements for the off-line digital orthoprinter. This model has been applied in simulation processing of frame and panoramic imagery over a wide range of camera orientations and terrain elevations. This work demonstrates that these algorithms can be applied in a practical field hardened system, using feasible design approaches for input film scanning, digital processing circuitry and orthophoto or rectified photo-generation.

3.2 System Model

The algorithm presently being considered for the generation of a digital orthophoto came from the work done by Control Data Corporation[1]. The algorithm is basically a digital simulation of the technique that is used by most commercially manufactured orthophoto instruments.

---

(1) Panton, D. J., Digital Orthophoto Study, Control Data Corporation, December 1975

To produce an orthophoto from a central perspective photograph or panoramic photograph two things are required. First, the input photo must be properly oriented relative to the scene depicted (recovery of exterior orientation elements). This can be done optically or digitally. In our system it is done digitally with the inputs required being the taking camera geometry. The second requirement is for a digital three-dimensional model of the object, such as a Digital Terrain Model (DTM) in the case of aerial photography.

The algorithm produces the orthophoto in model space on a projection plane for the reconstruction of the orthophoto image. Model coordinates are used to drive the differential rectification procedure with projections made from model space to input image space to obtain image density information. (See Figure 3.1).

For a given orthophoto pixel the procedure includes:

> Transform to model coordinates (model space)
>
> Interpolate the terrain data using the DTM
>
> Project into input photo space
>
> Convert to digital scan coordinates
>
> Sample density at that point creating orthophoto pixel

3.2.1 Frame Image Rectification

The algorithm basically works backwards, starting with an orthophoto pixel. The model coordinate is computed by converting the orthophoto pixel (I, J) into an (x, y) coordinate and scaling it to the stereo model:

$$x_m = \left(I - \frac{N_x}{2} - 1\right)(\Delta x)(\alpha)$$

$$y_m = \left(\frac{N_y}{2} - J + 1\right)(\Delta x)(\alpha) \tag{3.1}$$

where: (x_m, y_m): model coordinates

(I, J): orthophoto pixel

N_x, N_y: number of pixels in input photo

Δx : output pixel size

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IMAGE SPACE
(x_p, y_p)

DENSITY

ACQUISITION

P_2

P_3

MODEL
SPACE
(x_m, y_m)

P_4

P_1

ORTHOPHOTO
PIXEL (l, J)
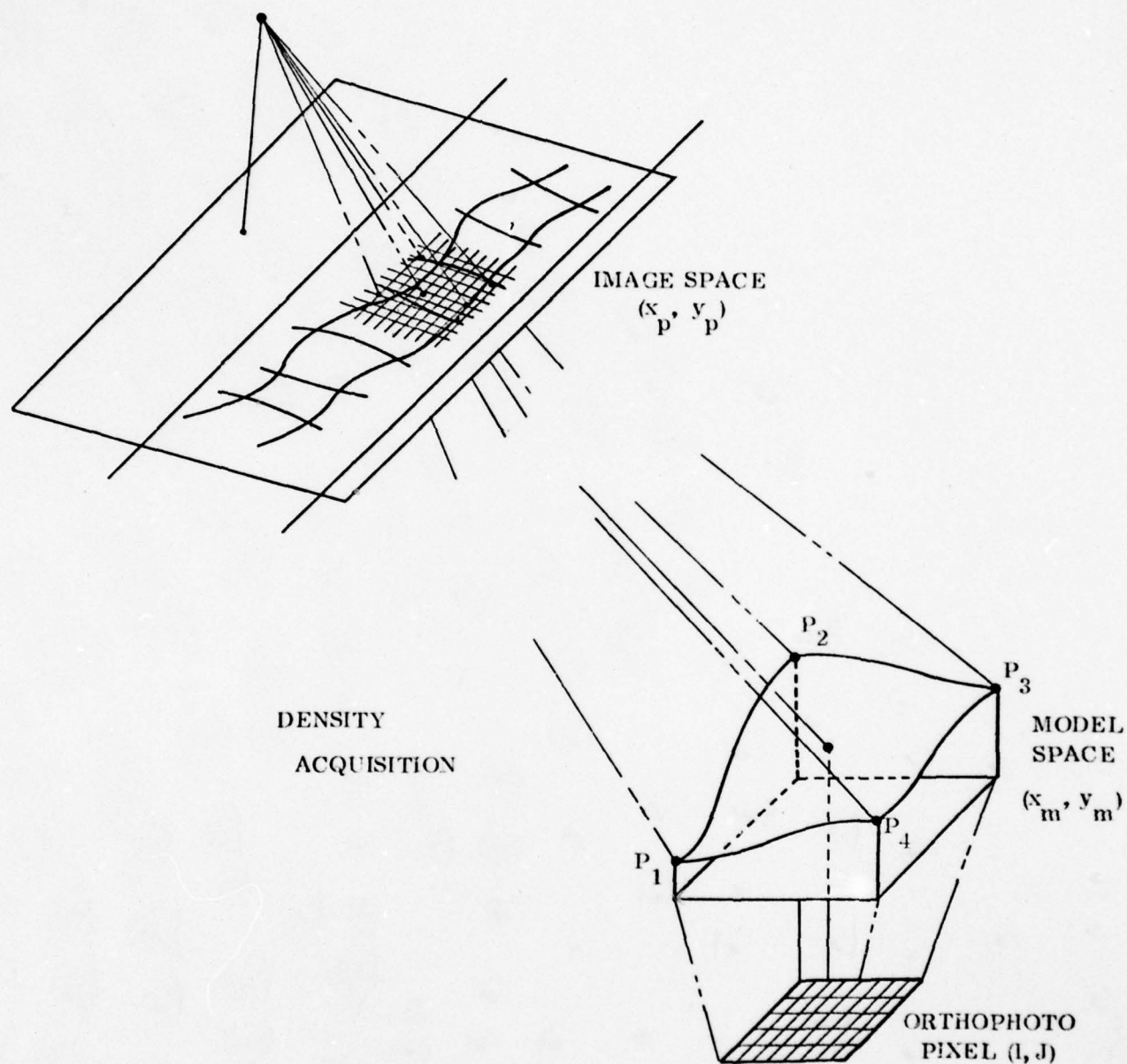
Figure 3.1 Digital Orthophoto Construction

Diagram from D. J. Panton, Digital Orthophoto Study, Control Data Corporation, December 1975

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$$\alpha = \frac{h}{H'SO}$$

h: model projection distance above datum

H':   flying height above datum

SO: orthophoto scale

It may be necessary at times to rotate the coordinates in orthophoto space to line up with the input photo space. As the algorithm now stands, orthophoto space is aligned with the DTM. This is satisfactory for most cases, but there are situations where the DTM and the photo are not closely aligned. In such a situation, it would be necessary to use a conformal coordinate transformation. This type of transformation is used to relate one rectangular coordinate system to another. In this case the relationship between the input photo and the DTM is required. Knowing the relationship, the orthophoto space can be transformed to coincide with input photo space. For cosmetic reasons, a limitation of the format to a rectangular area common to the DTM and photo would be desired.

Control points are needed for the alignment of the DTM and the input photo on the orthoprinter. The location and measurement of control points are discussed in Section 4.1.1. The conformal coordinate transformation is discussed in greater detail in this chapter.

After the model coordinates (x_m, y_m) are determined, the model elevation is determined from the digital terrain data (that is provided by another source) with an interpolating algorithm. The interpolation is a straight forward second order, two-dimensional, 4 point Lagrange interpolation. Given four points illustrated in Figure 3.2 of known planimetric positions (x_i, y_i) and elevations z_i, the elevation at another point of known (x_i, y_i) can be calculated as follows:

$z(x_1, y_1)$:   elevation of known points

(x_1, y_1):   coordinate of points

(x, y):   coordinate of interest
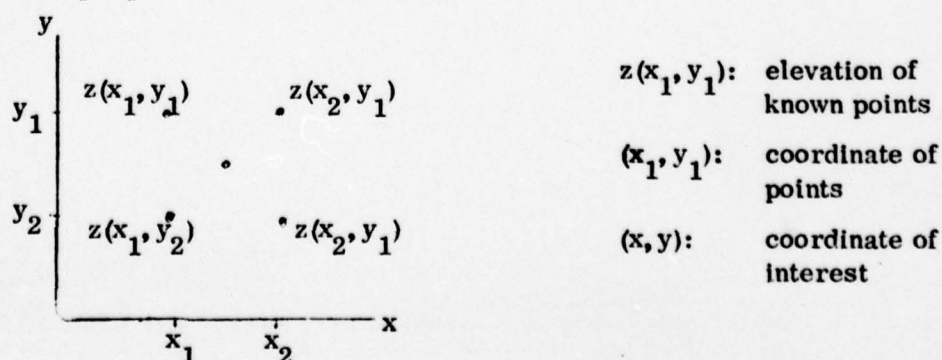
Figure 3.2 Model Coordinates

$$z(x,y) = \frac{(x - x_2)(y - y_2)}{(x_1 - x_2)(y_1 - y_2)} \; z(x_1, y_1) + \frac{(x - x_2)(y - y_1)}{(x_1 - x_2)(y_2 - y_1)} \; z(x_1, y_2) +$$

$$\frac{(x - x_1)(y - y_2)}{(x_2 - x_1)(y_1 - y_2)} \; z(x_2, y_1) + \frac{(x - x_1)(y - y_1)}{(x_2 - x_1)(y_2 - y_1)} \; z(x_2, y_2)$$

(3.2)

Now all three model coordinates (x_m, y_m, z_m) for the orthophoto pixel are known.

To perform differential rectification and rectification, the position and orientation of the camera platen must be known. The exterior orientation information required for this step may be known prior to beginning the rectification process or may be acquired from the input imagery. To determine the angular and positional orientation elements of a tilted frame photograph, the location of at least three control points recorded in the photograph must be known. With this data, methods such as the Church or Space Resection by Collinearity techniques may be used to determine the exterior orientation elements. For the present study, these coordinate parameters will be assumed known or available to the operator prior to the start of the rectification process. From this information, a rotation matrix can be computed relating input photo coordinates to model coordinates.

The rotation matrix m is defined as follows:

$$m = \begin{vmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{vmatrix}$$

(3.3)

A commonly used system defining the rotation matrix is the omega
(ω), phi (ϕ), and kappa (k) system (see Figure 3.3) The rotation matrix elements
are defined as follows:

$$m_{11} = \cos \phi \cos k$$
$$m_{12} = \sin \omega \sin \phi \cos k + \cos \omega \sin k$$
$$m_{13} = -\cos \omega \sin \phi \cos K + \sin \omega \sin k$$
$$m_{21} = -\cos \phi \sin k$$
$$m_{22} = -\sin \omega \sin \phi \sin k + \cos \omega \cos k$$
$$m_{23} = \cos \omega \sin \phi \sin k + \sin \omega \cos k$$
$$m_{31} = \sin \phi$$
$$m_{32} = -\sin \omega \cos \phi$$
$$m_{33} = \cos \omega \cos \phi$$
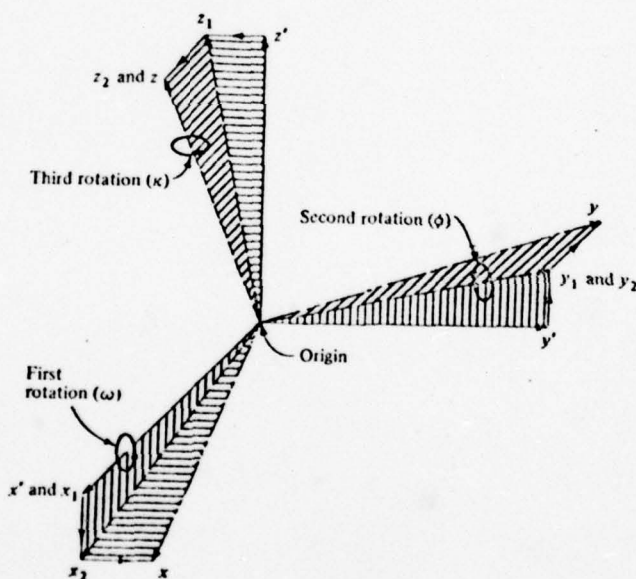
Figure 3.3 Omega, Phi, Kappa Rotation System *

Other angular systems sometimes used in analytical photogrammetry include
tilt, swing, and azimuth, **angles**, x-tilt, y-tilt, and heading, etc.

---

* Figure from Wolf, Paul, <u>Elements of Photogrammetry</u>, McGraw-Hill, 1974

It is now possible, using standard collinearity equations, to project from model space to input photo space and to correct scale for terrain elevation and camera geometry. There are other systematic errors that occur such as radial lens distortion, atmospheric refraction, film shrinkage, and earth curvature. These potential errors have been studied and are discussed in Section 3.2.3.

The projection to input image space is (see Figure 3.4):

$$xP = f \; \frac{(m_{11} x_m + m_{12} y_m + m_{13}(z_m - h))}{(m_{31} x_m + m_{32} y_m + m_{33}(z_m - h))}$$

(3.4)

$$yP = f \; \frac{(m_{21} x_m + m_{22} y_m + m_{23}(z_m - h))}{(m_{31} x_m + m_{32} y_m + m_{33}(z_m - h))}$$

where (x_m, y_m, z_m) are the model coordinates.

The camera station is assumed to coincide with the z-axis. This defines the (x, y) coordinate on the input film from which the density information is to be retrieved.

Each differential rectification technique has advantages and drawbacks. The major disadvantage of the chosen algorithm is the problem of multiple imaging. As seen in Figure 3.5 the same projected ray can emanate from more than one point on a very steep terrain surface.
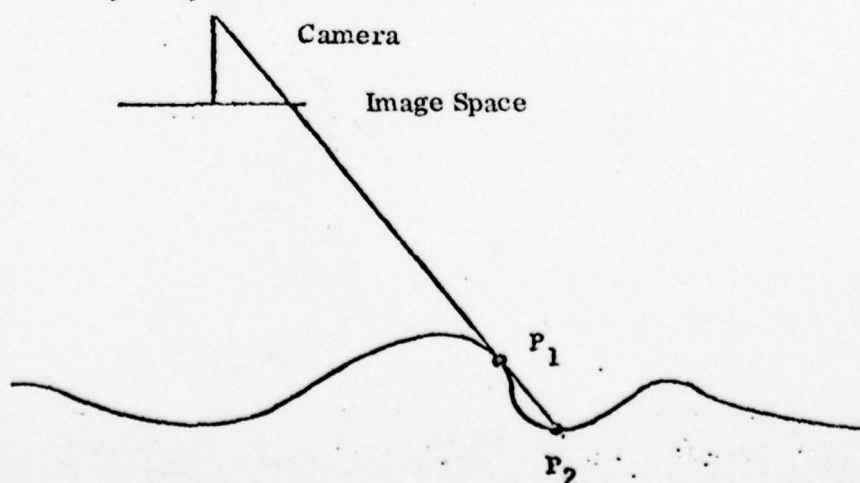
Figure 3.5 Multiple Imaging Geometry
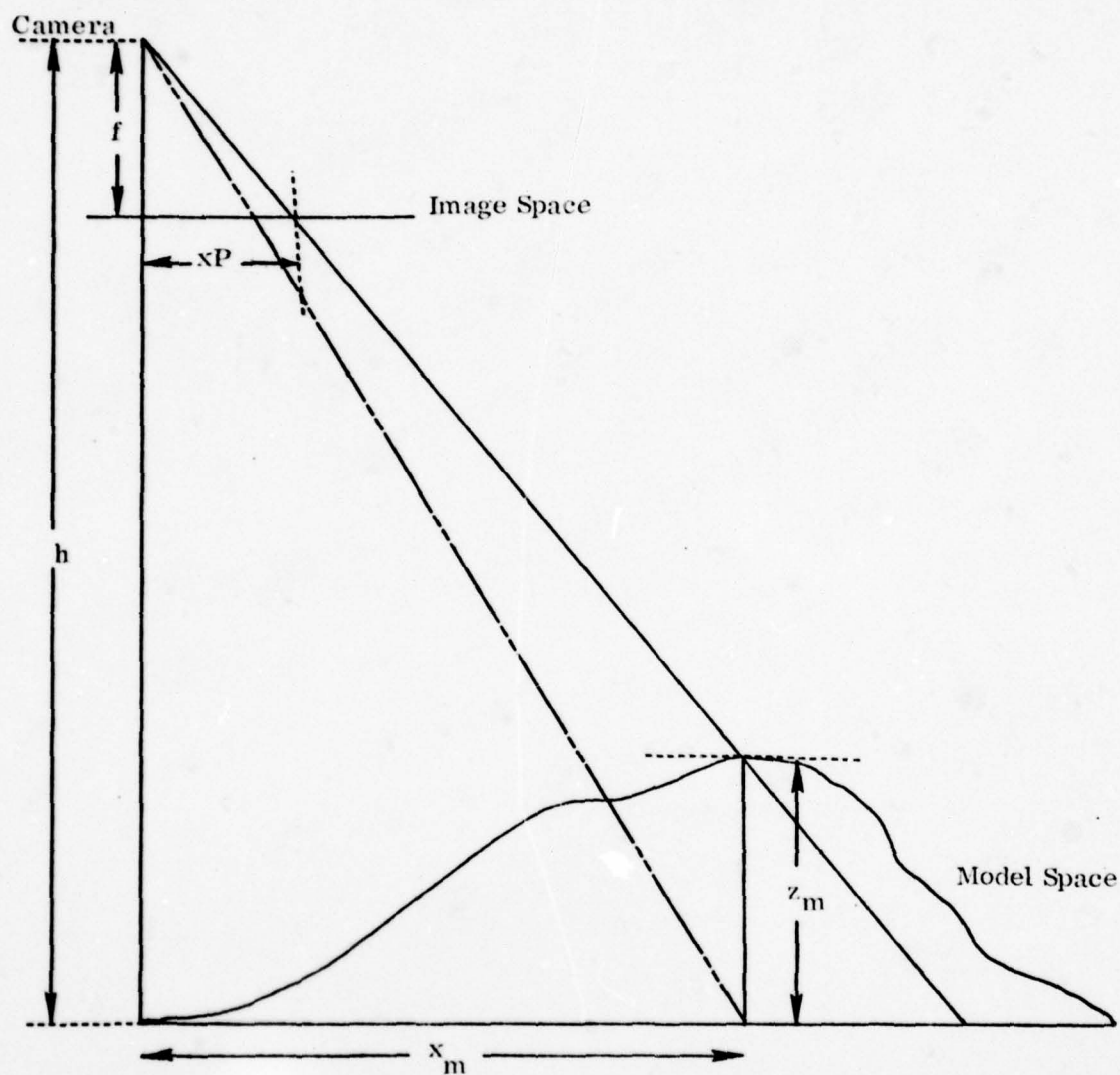
Figure 3.4 Cross-Section of Principle Plane showing projection from model space to image space. (Idealized)

The algorithm does not permit grey scale "holes" to occur, because of the interpolation process that takes place. This algorithm assures that for every pixel position of the orthophoto there will be a distinct grey level. This applies to the panoramic case as well.

3.2.2 Panoramic Rectification

A panoramic photograph is a picture of a strip of terrain taken transverse to the direction of flight. The exposure is made by a specially designed camera which scans laterally from one side of the flight path to the other. The lateral scan angle may be as great at 180°, in which case the photograph contains a view of the terrain from horizon to horizon. Rarely would a photograph of this extreme scan angle be required for rectification to an orthophoto.

Panoramic rectification requires an additional transformation over frame rectification. The input photo coordinates first computed assuming a frame camera, are then converted into the distorted panoramic input photo coordinates. (See Figure 3.6)

The transformation is as follows:

$$
\begin{aligned}
\psi &= \tan^{-1}[yP/f] \\
xP' &= (xP)(\cos \psi) \\
yP &= (f)(\psi)
\end{aligned}
\tag{3.5}
$$

(xP, yP) : input photo coordinates calculated for frame photo using Equation (3.4)

(xP', yP') : input photo coordinates calculated for panoramic photo

ψ : panoramic scan angle

f : focal length of taking camera (frame or pan)
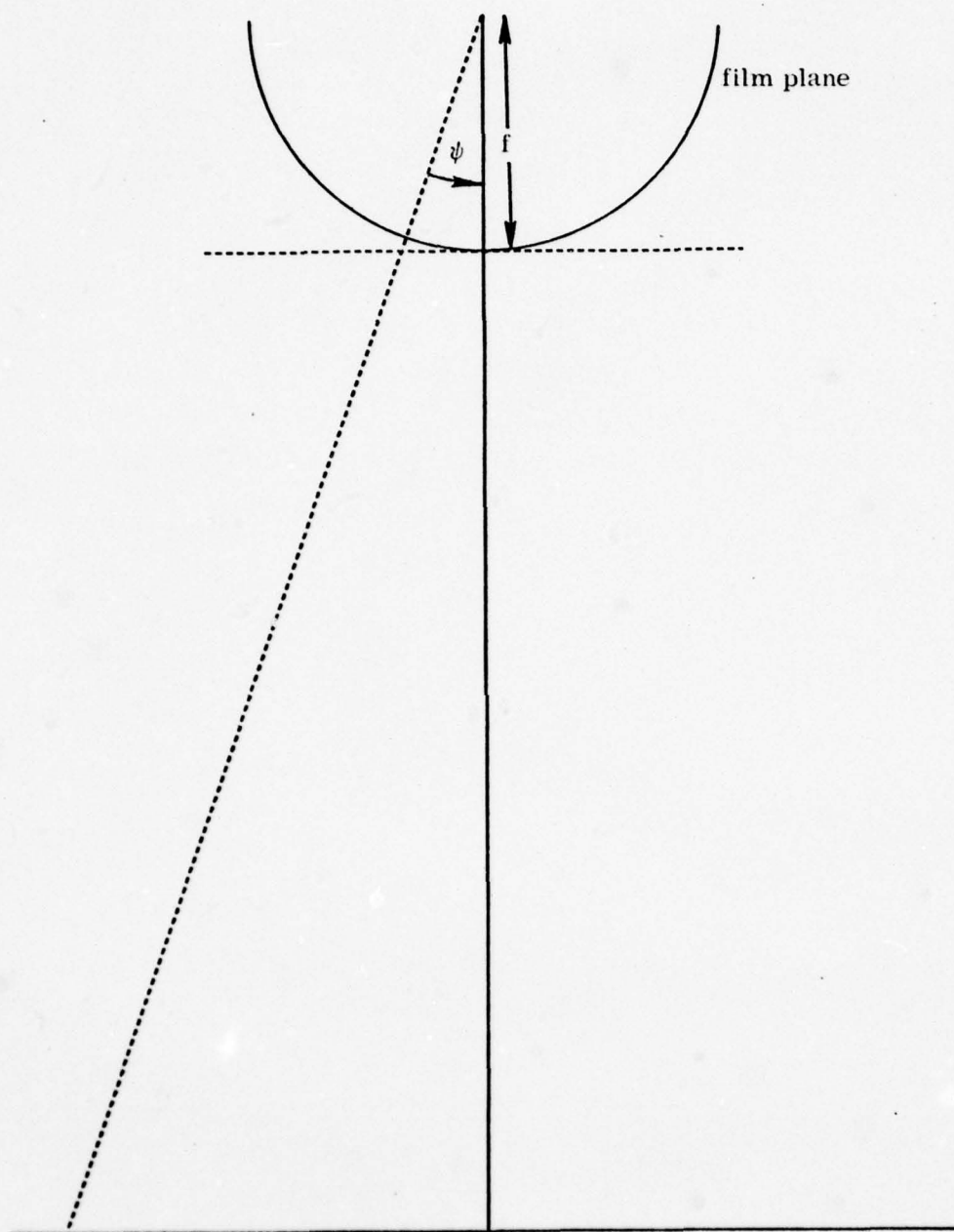
Figure 3.6 Geometry for Panoramic Photography

If a square grid on flat ground is photographed with a panoramic camera in vertical orientation, panoramic distortions produce the well known trapezoidal grid pattern shown in Figure 3.7.
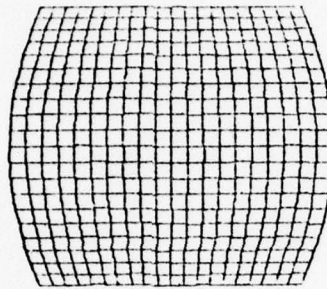
Figure 3.7 Panoramic Distortion

In addition to panoramic distortion, pan camera geometry introduces several other types of distortion including:

> Scan positional distortion – displacements caused by forward motion of aircraft as the lens scans

> Image motion compensation – displacements caused by translation of lens or negative surface to compensate for motion during exposure.

These distortions, produced by the camera geometry can be compensated for by a third-order polynomial transformation, where the coefficients of transformation are determined by a number (around 20) of control points.

3.2.3 Orientation on Scanner

The rectification and differential rectification algorithms correct for these distortions and defines the location where the density information for the orthophoto pixel exists on the input photograph. Knowing this information, the location of that spot must be found on the scanner that is digitizing the input photo. This involves a conformal coordinate system transformation. Known fiducial or control points are located on the film (mounted on the scanner) and these coordinates (see Figure 3.8) define the input photo coordinates with respect to the scanner coordinates.
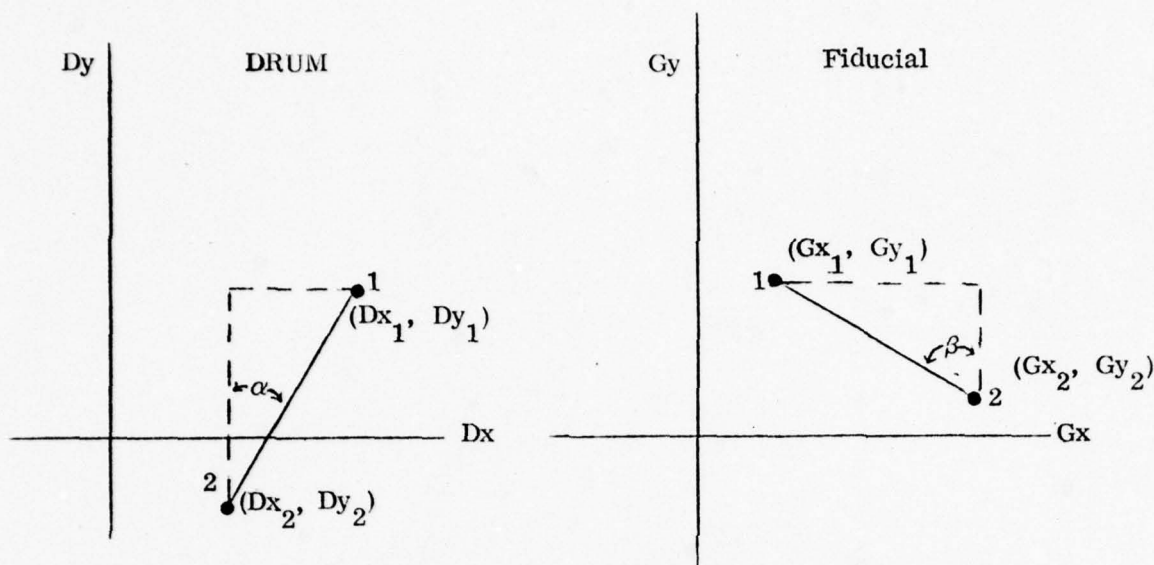
Figure 3.8 Geometry for Input Photo to Drum Transformation

Two fiducial point locations are necessary for the transformation. There are three steps involved in the transformation:

1. scale change, s
2. rotation, Θ
3. two translations, XOFST, YOFST

These are defined by:

(1) Scale Change:

$$S = \sqrt{\frac{(D_{x_2} - D_{x_1})^2 + (D_{y_2} - D_{y_1})^2}{(G_{x_2} - G_{x_1})^2 + (G_{y_2} - G_{y_1})^2}} \qquad (3.6)$$

(2) Rotation:

$$\alpha = \tan^{-1}\left(\frac{G_{x_1} - G_{x_2}}{G_{y_1} - G_{y_2}}\right) \qquad (3.7)$$

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$$\beta = \tan^{-1}\left(\frac{D_{x_2} - D_{x_1}}{D_{y_1} - D_{y_2}}\right) \tag{3.7}$$

$$\theta = \alpha + \beta = \text{Rotation angle}$$

(3) Translation:

$$\text{XOFST} = D_{x_1} - (S)(\cos\theta)G_{x_1} - (S)(\sin\theta)G_{y_1}$$

$$\text{YOFST} = D_{y_1} + (S)(\sin\theta)G_{x_1} - (S)(\cos\theta)G_{y_1} \tag{3.8}$$

The equations for conversion are given by:

$$D_x = (S)(\cos\Theta)G_x + S(\sin\Theta)G_y + \text{XOFST}$$

$$D_y = -(S)(\sin\Theta)G_x + S(\cos\Theta)G_y + \text{YOFST} \tag{3.9}$$

Another way to do this transformation, which is somewhat easier, is to parametize the variables. In the former transformation the arctan function would lead to sign problems depending on which quadrant the control points were in. The equations for conversion are given by:

$$D_x = aG_x + bG_y + C$$

$$D_y = -bG_x + aG_y + D \tag{3.10}$$

where

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} (G_{x_1} - G_{x_2}) & (G_{y_1} - G_{y_2}) \\ (G_{y_1} - G_{y_2}) & -(G_{x_1} - G_{x_2}) \end{bmatrix}^{-1} \begin{bmatrix} D_{x_1} - D_{x_2} \\ D_{y_1} - D_{y_2} \end{bmatrix} \tag{3.11}$$

To solve for C, and D, knowing a and b, we can use Equation (3.10).

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$$C = D_{x_1} - aG_{x_1} - bG_{y_1}$$

(3.12)

$$D = D_{y_1} + bG_{x_1} - aG_{y_1}$$

Since the scanner coordinates D_x and D_y will probably be non-integral numbers (i.e., not fall directly on 1 pixel) a 4-point interpolation of the density levels of the nearest pixels will be required as the final step (see section 3.2.1).

3.2.4 Analysis of Systematic Errors and Their Effects on Photogrammetric Accuracy

No matter how image coordinates are measured on a photographic image, certain errors will always be present. These sources of errors are:

1. shrinkage of film
2. radial lens distortions
3. atmospheric refractions
4. earth curvature distortions

These distortions can be corrected mathematically; however, depending on the accuracy of the work they may sometimes be neglected.

In this study for image rectification, we consider output image resolution on the order of 10 cy/mm. The sample spacing required to obtain this resolution is defined by the sampling theorem:

$$x = \frac{1}{2 \text{ (res)}} = \frac{1}{20} = 0.050 \text{ mm}$$

In studying the image errors, a distortion that does not exceed the sample period can be considered a small error and can be neglected.

3.2.4.1 Shrinkage Correction

Typical film shrinkage values range from almost negligible amounts to about 0.2 percent. The amount of shrinkage or expansion can be

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determined by comparing measured photographic coordinates of fiducial marks with their corresponding values determined in camera calibration.

There is controversy as to whether film shrinkage can be neglected. There are two important reasons for this:

1. Film processing critically impacts on shrinkage and should be performed without any deviation from the recommended procedure.

2. The quality of aerial film dimensional stability is not as good as the literature indicates.

Depending on the type of processing and film being used, testing will indicate whether film distortion correction is necessary.

3.2.4.2 Radial Lens Distortions

A curve (Figure 3.9) for radial distortion of a Zeiss lens is given in μm vs. radial distance from the principle point. It can be seen that nowhere does the distortion become larger than ±5μm, clearly smaller than our resolution element. In general, good quality lenses have minimal radial distortion by design.

Radial lens distortion curve
camera no. 98188
Zeiss RMKA 15-23
CFL = 152.44 mm
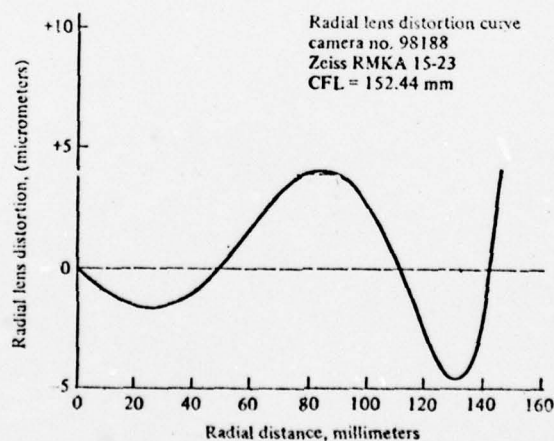
Figure 3.9 Radial-Lens Distortion Curve
for the Zeiss Pleogon Aerial Camera Lens*

---

* Graph from Wolf, Paul, Elements of Photogrammetry, McGraw-Hill Inc. 1974.

3.2.4.3 Atmospheric Refraction

The density of the atmosphere and thus the index of refraction decreases with increased altitude. Because of this, light rays are differentially diffracted and do not travel in straight lines through the atmosphere (see Figure 3.10).
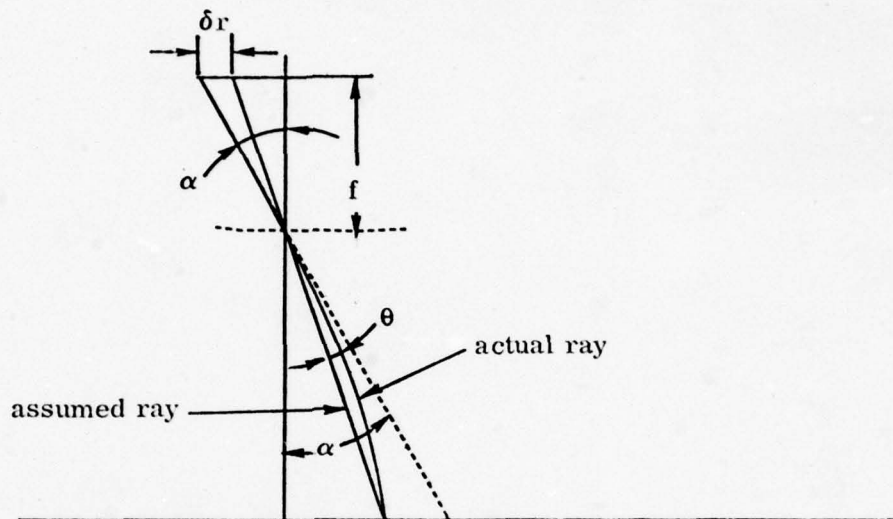
Figure 3.10 Geometry of Atmospheric Refraction Correction

To calculate the displacement due to refraction, the following equations are used:

$$\delta r = \frac{f\,\theta}{\cos^2 \alpha} \qquad\qquad \alpha = \tan^{-1}\left(\frac{r}{f}\right) \qquad\qquad r = \sqrt{x^2 + y^2} \qquad f = \text{focal length} \qquad (3.14)$$

A nomograph shown in Figure 3.11 illustrates that no distortions exceed $20\mu\text{m}$, so atmospheric refraction can be neglected within the limits of the parameters described (scale factor of 1:60,000 and radial distance of 140mm). However, for a high oblique photograph these distortions would require correction.

Radial distortions due to atmospheric refraction for vertical photos taken with a 6-inch (150 mm) focal length camera and various flying heights and ground elevations above MSL
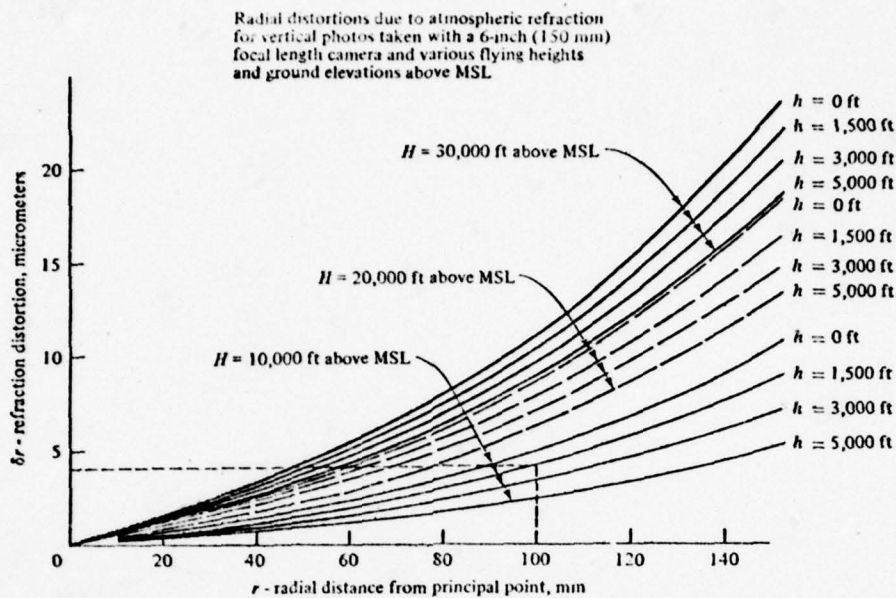
Figure 3.11 Nomograph for Radial Distortions
due to Atmospheric Refraction*

3.2.4.4 Earth Curvature

In calculating positions of points on a photograph, it may be necessary to correct for image distortions caused by curvature of the earth (Figure 3.12).

The correction for the curvature is as follows:

$$dr = \frac{H' r^3}{2 R f^2} \qquad (3.15)$$

where

R: radius of earth

f: focal length of camera

H': camera height.

---

* Graph from Wolf, Paul, Elements of Photogrammetry, McGraw-Hill, 1974.

20
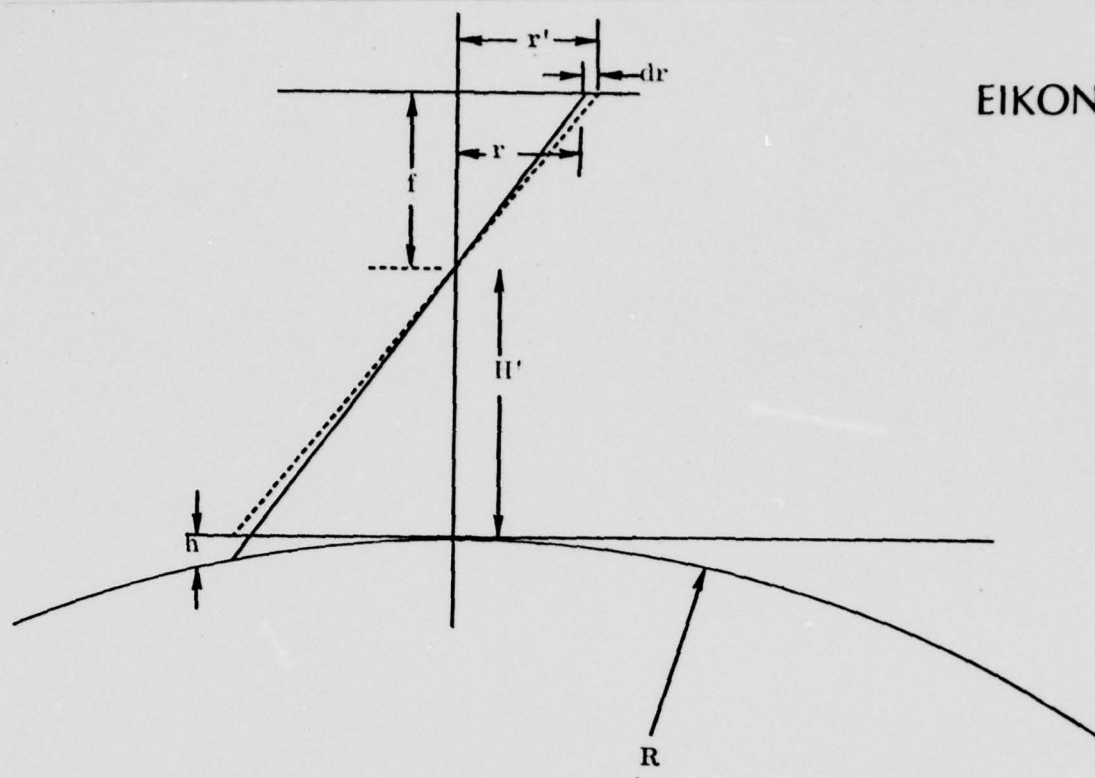
Figure 3.12   Geometry for Earth Curvature Correction

Another nomograph shown in Figure 3.13, illustrates that with a scale* of less than 1:30,000 can be neglect this distortion.   For a scale of 1:40,000 this distortion can be neglected up to a radial distance of 130mm.

Radial distortions due to earth curvature for vertical photographs taken with a 6-inch (150 mm) focal length camera at various flying heights above ground
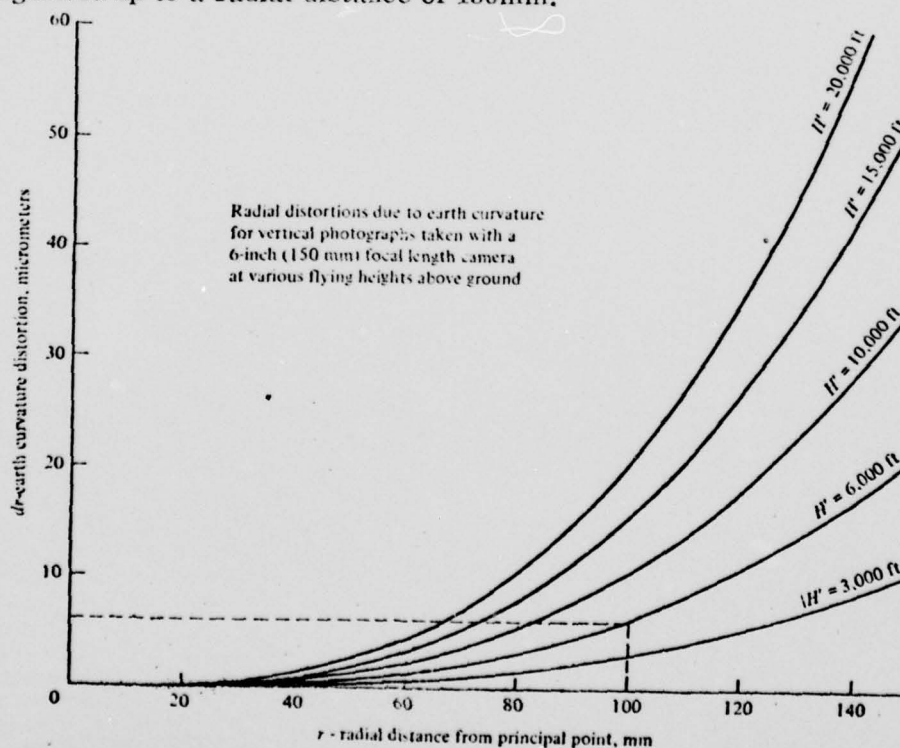
Figure 3.13   Nomograph for Radial Distortions Due to Earth Curvature **

* Scale is the ratio of height to focal length
** Graph from Wolf, P.R., Elements of Photogrammetry, McGraw-Hill, Inc. 1974

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If the DTM data is expressed in a geodetic system where the curvature of the earth is accounted for, no further correction is required.

The above analysis on system errors was performed for frame photography. Panoramic photography would conform to the analysis; however, film shrinkage could become a factor of more concern for a long frame.

3.3 Orthophotographic Equipment Review

Differential rectification (correction for scale changes due to terrain height and camera tilt) is produced in one of two manners; optical or opto-mechanical projection and electronic. In the optical projection of an orthophoto image, elements are shaped and magnified via zoom optics and prisms to produce the orthophoto on film. In the opto-mechanical means of production, the orthophoto is produced by moving the recording film plane up and down to account for scale changes. The electronic machines do the differential rectification electronically and the output is on a Cathode Ray tube which has resolution limitations. Some instruments provide computer assistance to correct for earth curvature, atmospheric refraction, film deformation, taking lens distortion, etc. The point is that they still use optical or opto-mechanical means to introduce the corrections obtained by the computer.

Most of the orthophoto instruments operate in two modes; on-line and off-line. In the on-line mode, the machine must scan the stereo model and produce terrain elevation data for the differential rectification and expose the orthophoto at the same time. In an off-line mode, the terrain data can be recorded for orthophoto production at a later time.

In an on-line mode, there is a trade-off between speed and accuracy. If the machine scans the stereo model at a rapid speed, there are problems with an operator accurately following the terrain in mountainous areas, so he will usually slow the machine down to increase his ability to follow the terrain. Thus, the orthophoto takes longer to produce. In the off-line mode, the operator

can take his time profiling and then the orthophoto can be produced later, with the stored profiles, at a constant rapid speed.

These machines profile and expose the orthophotos with a rectangular slit in a raster fashion. Therefore, one terrain elevation data point corresponds to a large rectangular area on the ground. This is referred to as zero order differential rectification.

In an on-line mode, the printing area, being a slit, introduces some error. When the machine is used off-line, a narrower slit might be used if the terrain data can be interpolated. This would be a higher order of differential rectification.

One machine studied that performed higher order differential rectification was the Zeiss GZ1 orthoprojection system. An accessory fiberoptic interpolation ring introduces an inclination of the projection surface (across the scanning path) equivalent to the ground slope by using the stored profiles.

An option most machines exhibited was the ability to plot elevation contours separately or on the orthophoto. With these machines, the input pair of stereo photographs must be oriented properly. This occurs in three steps: Interior, Relative and Absolute Orientation.

Interior Orientation: Placing the transparencies in the projectors and adjusting them so the emerging rays are the same as those that entered the camera lens during exposure.

Relative Orientation: Orient the two projectors so their exact angular orientation to one another in the projectors is the same that the negatives had in the camera at the time of exposure, thus a stereo model is formed.

Absolute Orientation: The model is brought to the desired scale and leveled with respect to a reference datum.

In most of the machines the three operations are performed manually. There is one electronic machine which has made a breakthrough in image correlation techniques so as to automate most of the orientation process and the profiling process. This is the Gestalt Photomapper GPM2. A description of each machine studied appears in Appendix A.

From a review of the available equipment and an analysis of requirements, we have concluded that a digital orthoprinter design is best for field use for many reasons. First, a digital system can be made to operate extremely fast by its very nature. Secondly, in comparison to an opto-mechanical piece of hardware, a digital system will be much smaller and more applicable to field use. Depending on the method used to digitize and output the photo, the digital system has very few moving parts and is less susceptible to the less than optimal conditions that can be expected in field use. For field use the off-line operation is very attractive. Being off-line, the operator needs not attend the machine while it is operating. He needs only to input certain parameters, measure some control points and initiate the system operation. The machine does the rest.

3.4 Computer Simulations

3.4.1 Scanning Array Size Estimation

The concept of an off-line digital orthoprinter involves an input image scanner, a computer to process the data, and an output writer. The input scanner in our system must be able to "view" a significant area at one time for reconstruction of the orthophoto. The size of the input scanning array depends on the distortions and displacements due to terrain height and camera geometry.

To get some idea of the magnitude of these distortions a computer program was written to calculate and plot the displacements of orthophoto pixels. The program takes a rectangular grid of lines (Figure 3.14 top) with a cross in the center where the cross elevation above the grid lines is a control parameter.

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The program rectifies the whole image but only differentially rectifies (compensates for terrain height) the cross in the middle. This evaluation program actually performs rectification in reverse; a flat grid with no terrain information is tilted and warped as in the lower plot in Figure 3.14. From the plots we can see the pixel shifts associated with various camera geometries and terrain elevations.

In practical applications tilt angles are maintained to a few degrees. Terrain elevations are kept to about 20% of the flying height. Depending on swing and azimuth angles, the pixel shifts in the orthophoto can be up around two thousand pixels. The program does the same for panoramic rectifications (see Figure 3.15).

From this information we note that an image scanner must access a large area of the input photo to include pixel shifts from distortions in a short period of time. With a large one-dimensional array (1024 pixels) on a drum scanner, an entire input photo (assuming a "9 x 9" format) can be scanned in 4-6 revolutions of the drum scanner. A more detailed hardware description is given below in Chapter 4.

More grid line plots can be found in Figures 3.16 - 3.23. The tilt angles in these plots are exaggerated to enhance the distortion effects. The plots cover both frame and panoramic cases, with tilt and swing angles and terrain elevation. The terrain elevation, or heights as labelled on the plots, correspond to 5, 15, and 25% of camera flying height. The incomplete appearance of some of the plots is due to the scales being too small. The Nadir point is always maintained directly over the center of the grid area.

3.4.2 Rectification Simulation

A test was performed on the rectification algorithms. A digital test image was produced by photographing a set of annular rings with a cross etched in the middle. Different camera geometries were assumed and digital photographs were produced with various tilt, swing, and azimuth angles. These simulations were done with a simulated scanning array of only 32 x 32 pixels. The shrinking of the pictures is due to the fact that the large camera angles shift the orthophoto pixels outside the "look" area of the scanning array (see Figure 3.24).
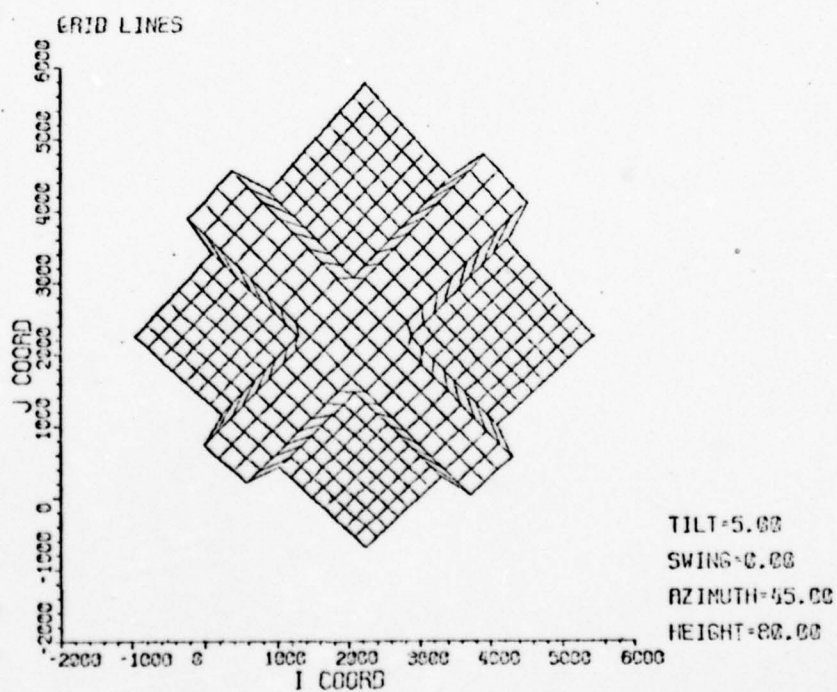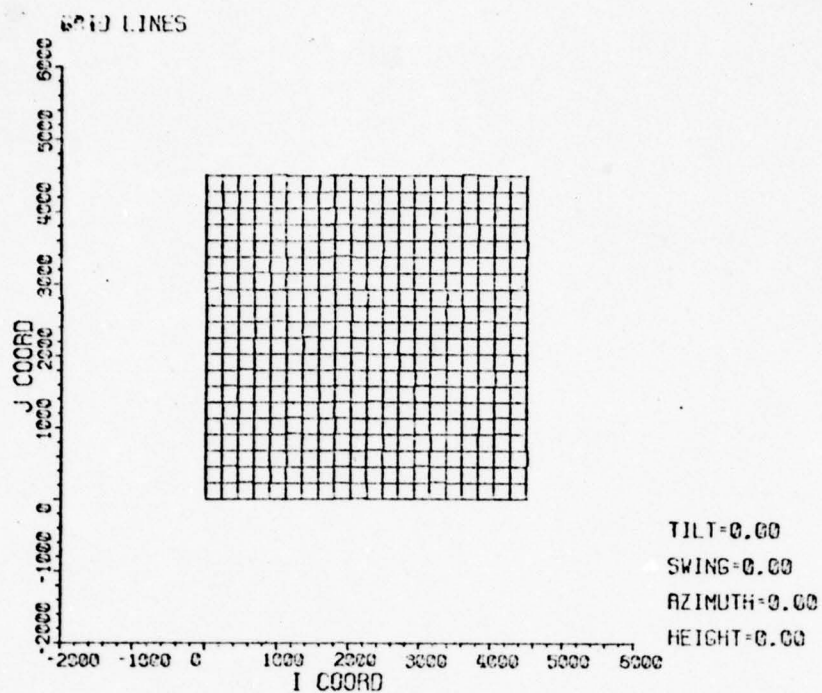
Figure 3.14 Output of Computer Program DIST for Frame Photography

GRID LINES

TILT=0.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=0.00

GRID LINES

TILT=5.00
SWING=45.00
AZIMUTH=0.00
HEIGHT=80.00
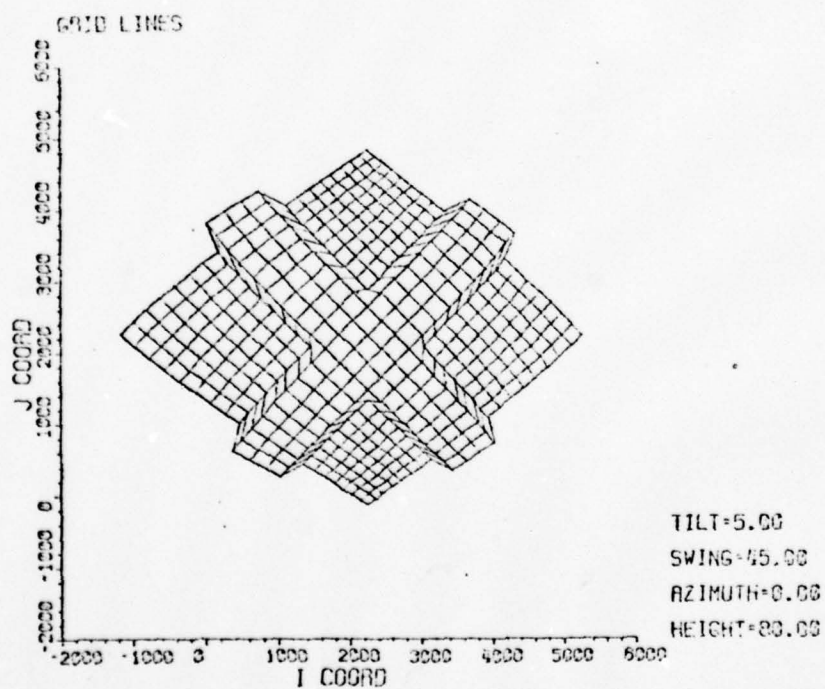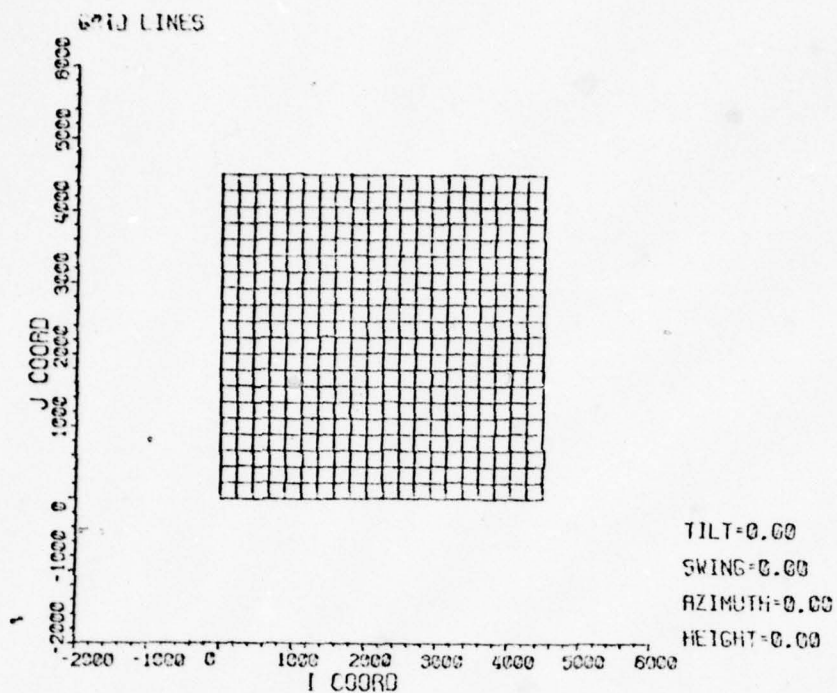
Figure 3.15 Output of Computer Program DIST for Panoramic Photography

27
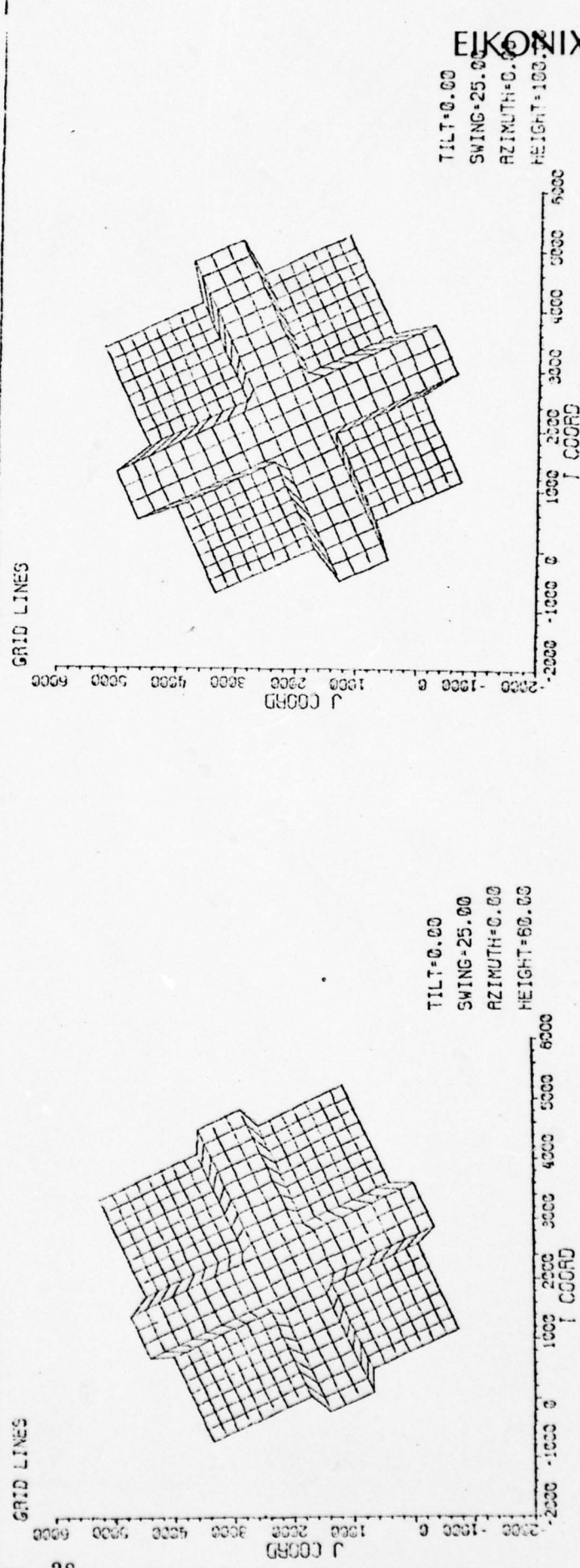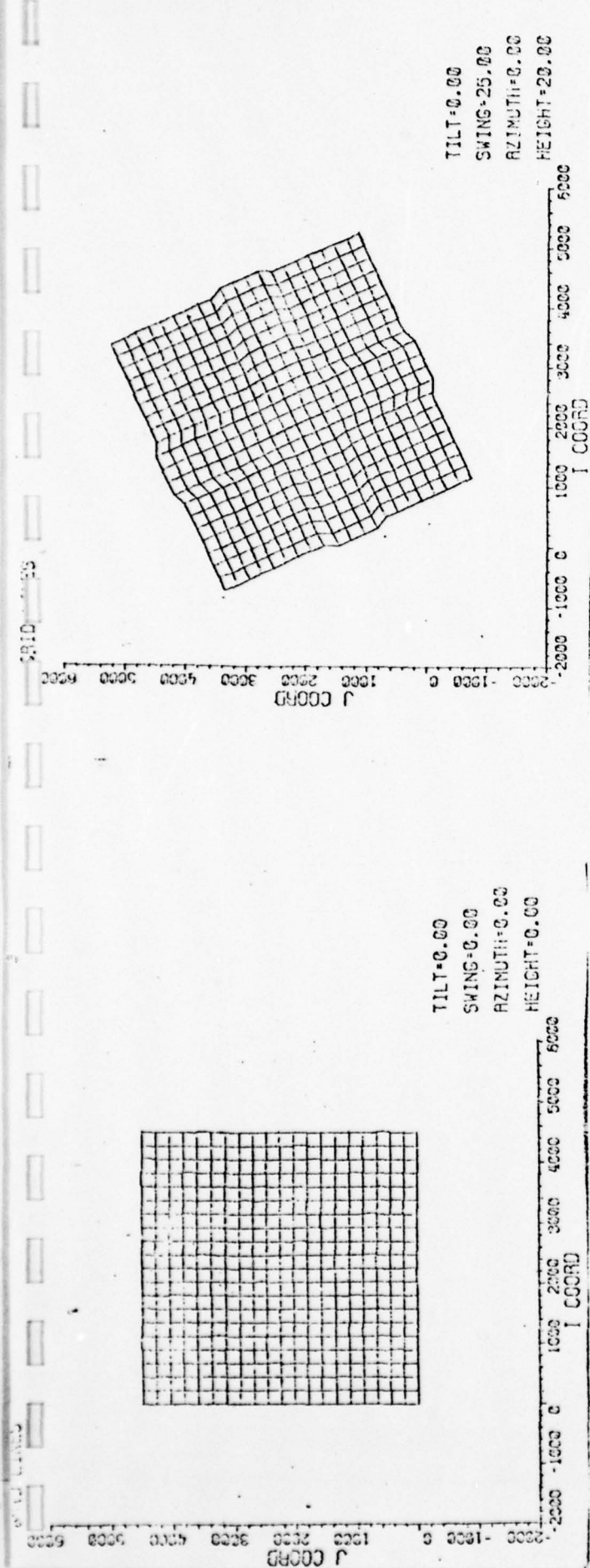
Figure 3.16   Grid Lines for Frame Photography. No Tilt, 25° swing
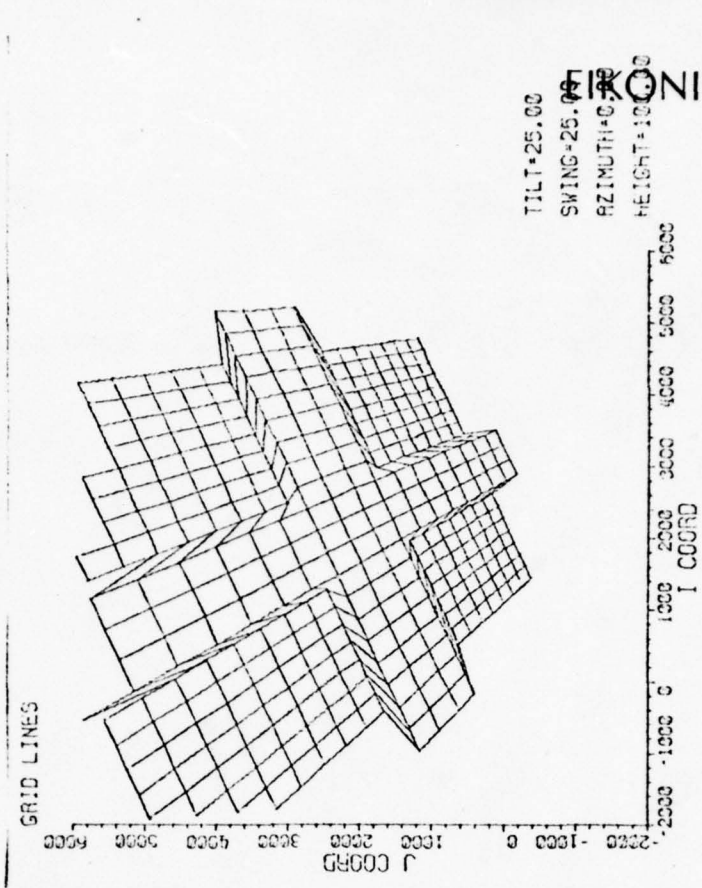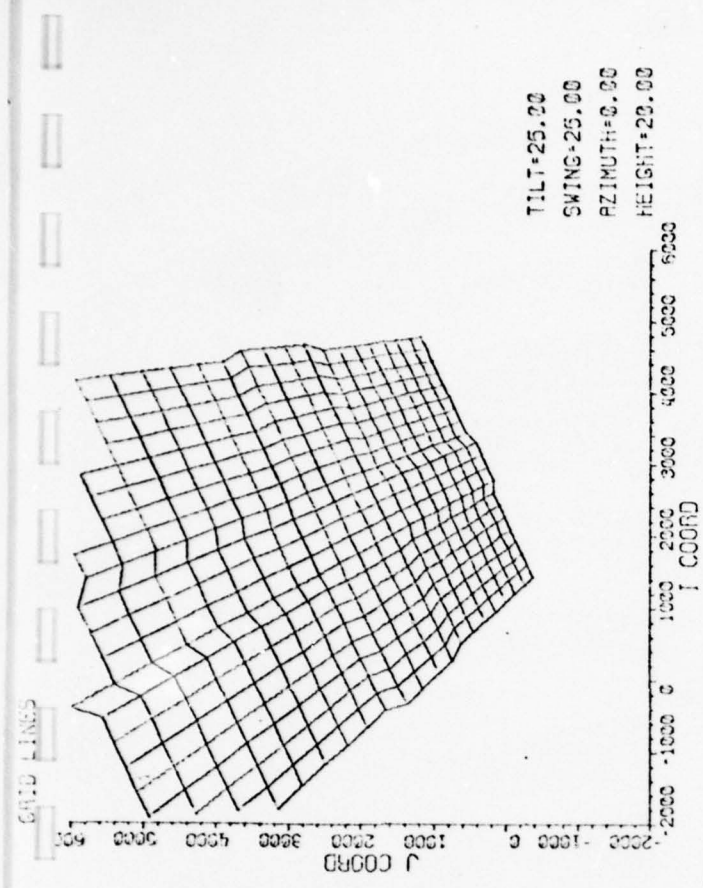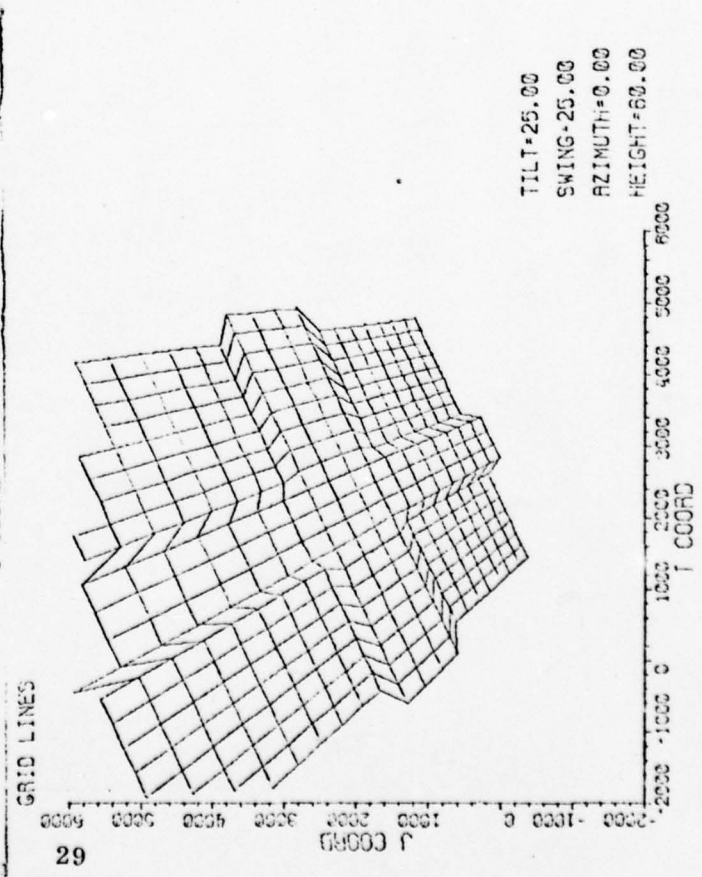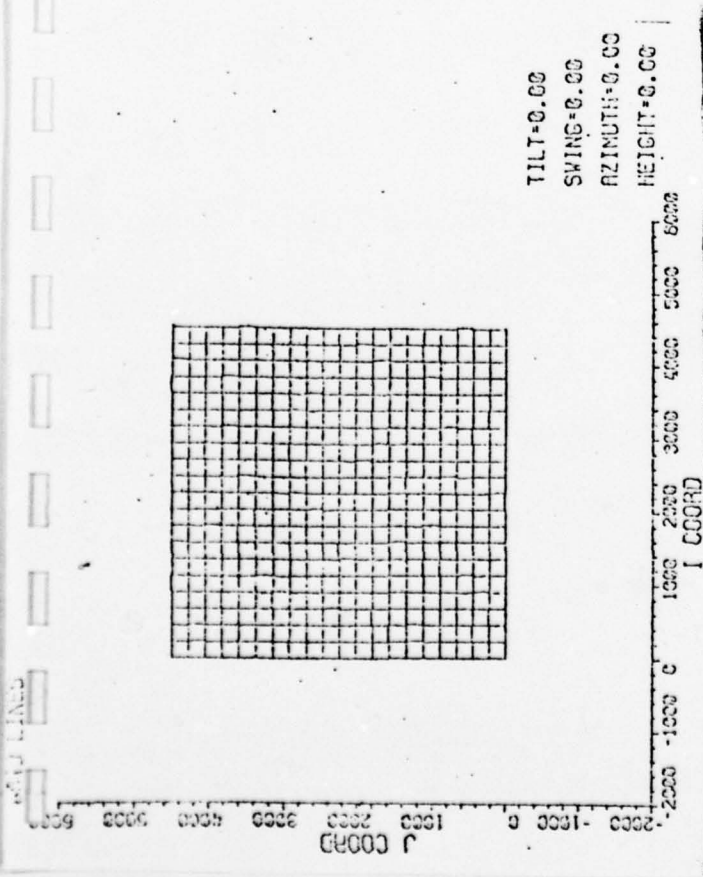
Figure 3.17   Frame Photography.   25° Tilt, 25° Swing

Figure 3.18   Panaromic Photography. No Tilt, 25° Swing

EIKONIX®

TILT=0.00
SWING=25.00
AZIMUTH=0.00
HEIGHT=20.00

TILT=0.00
SWING=25.00
AZIMUTH=0.00
HEIGHT=60.00

TILT=0.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=0.00

TILT=0.00
SWING=25.00
AZIMUTH=0.00
HEIGHT=60.00

GRID LINES

J COORD

I COORD

30
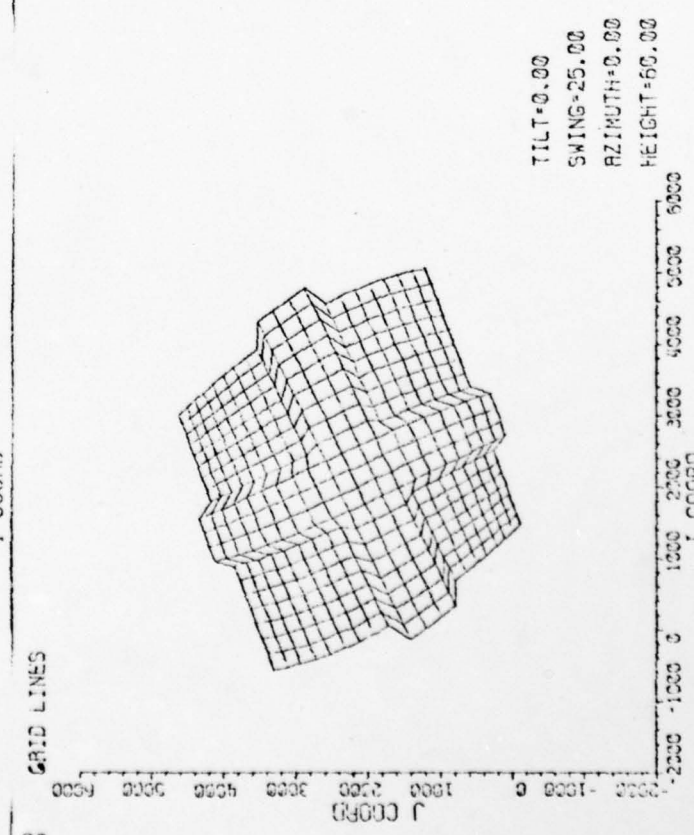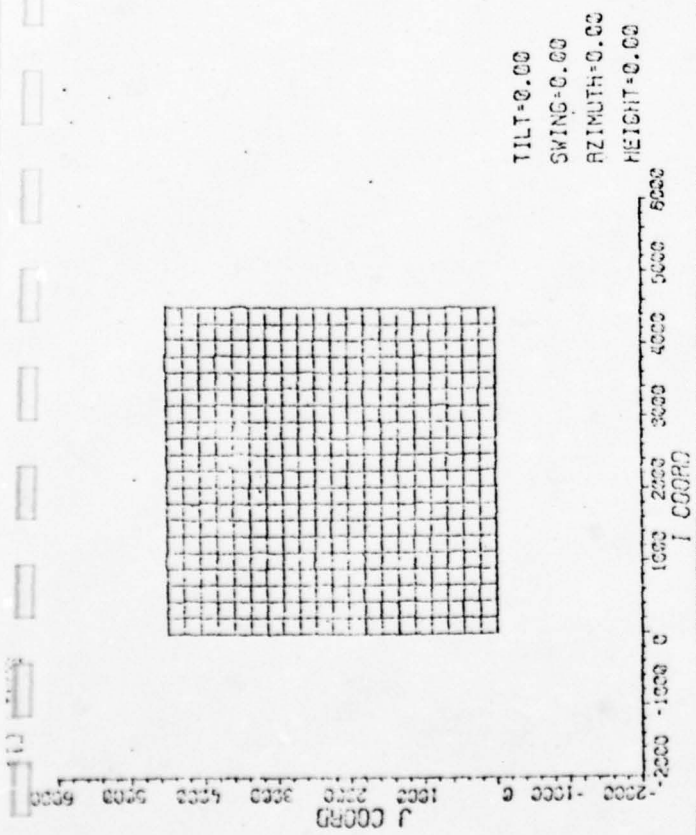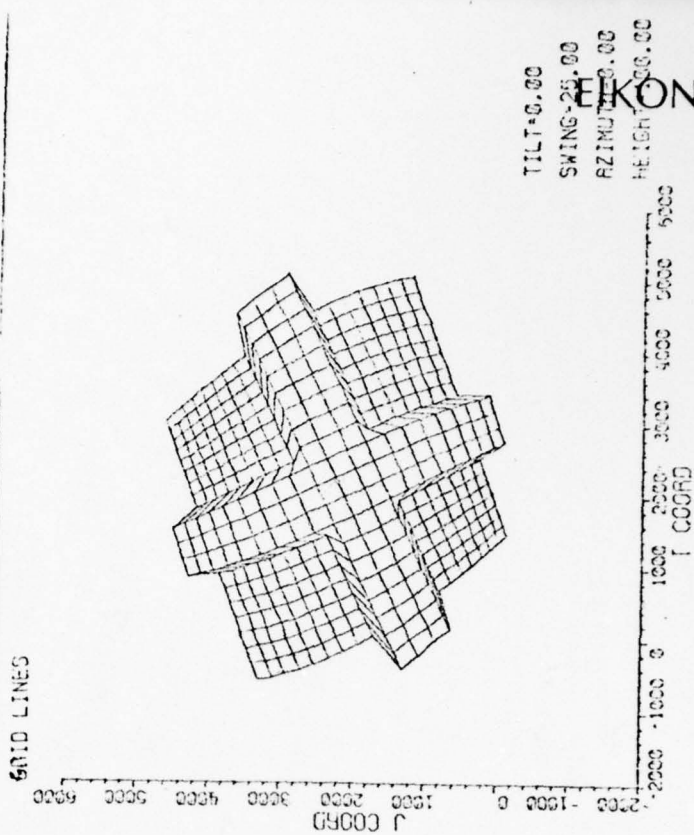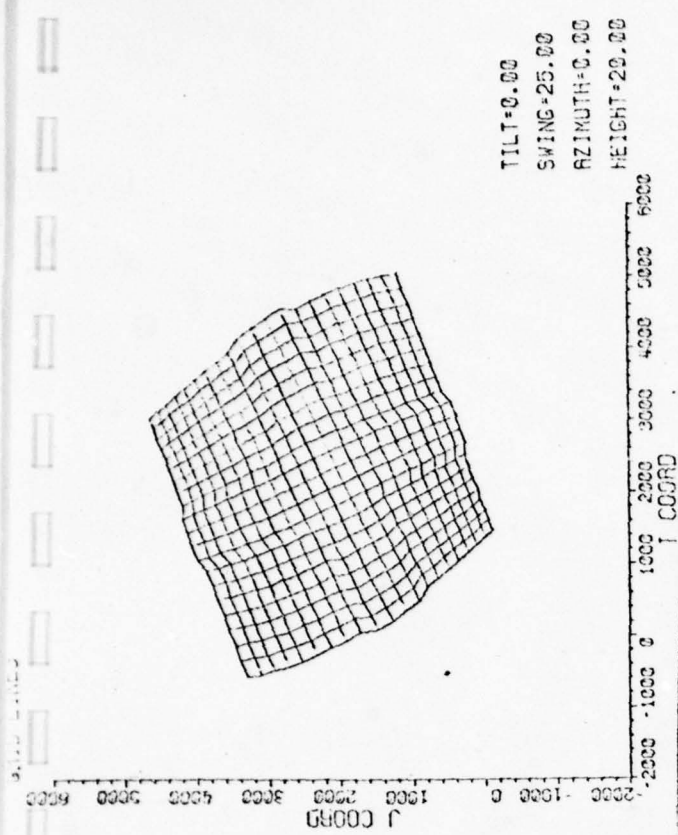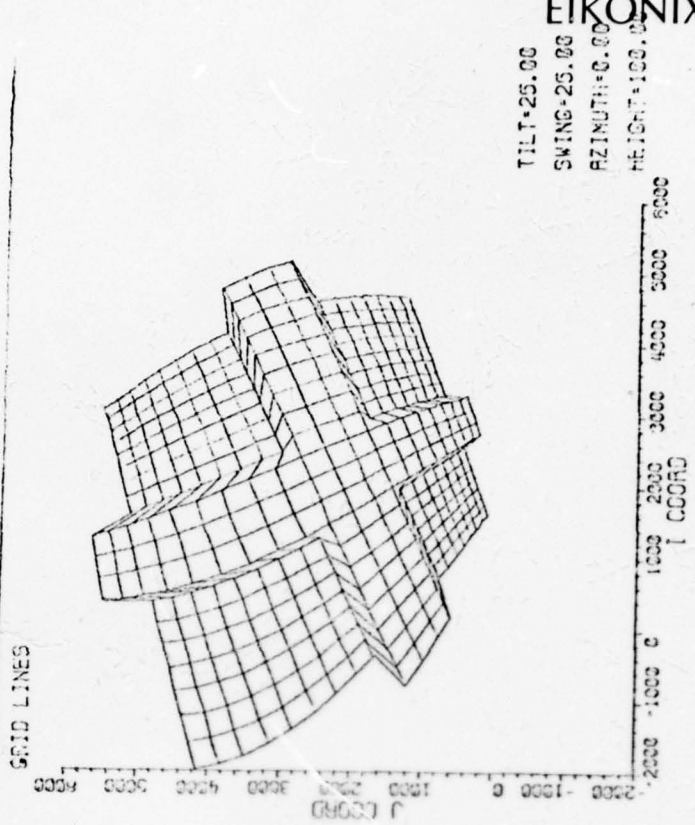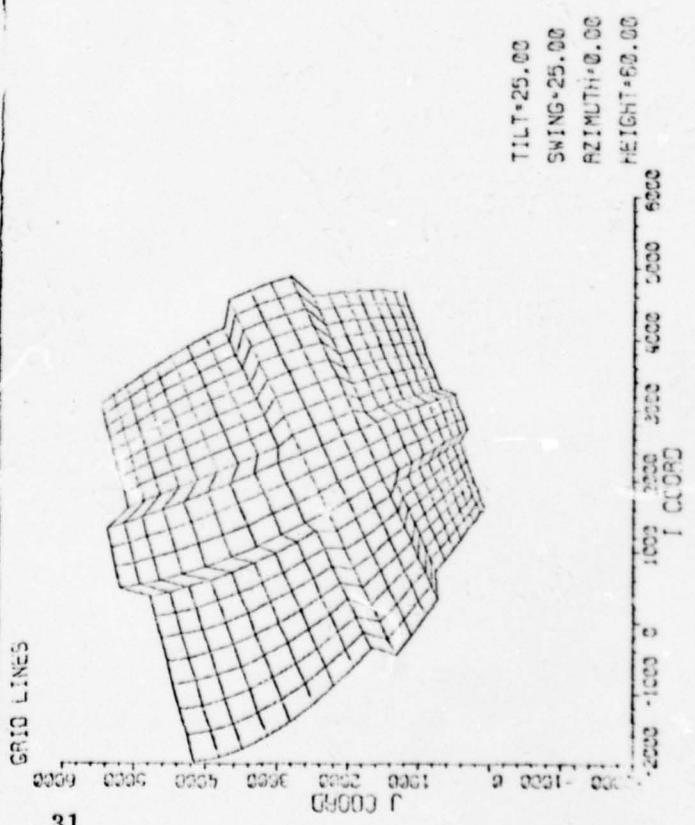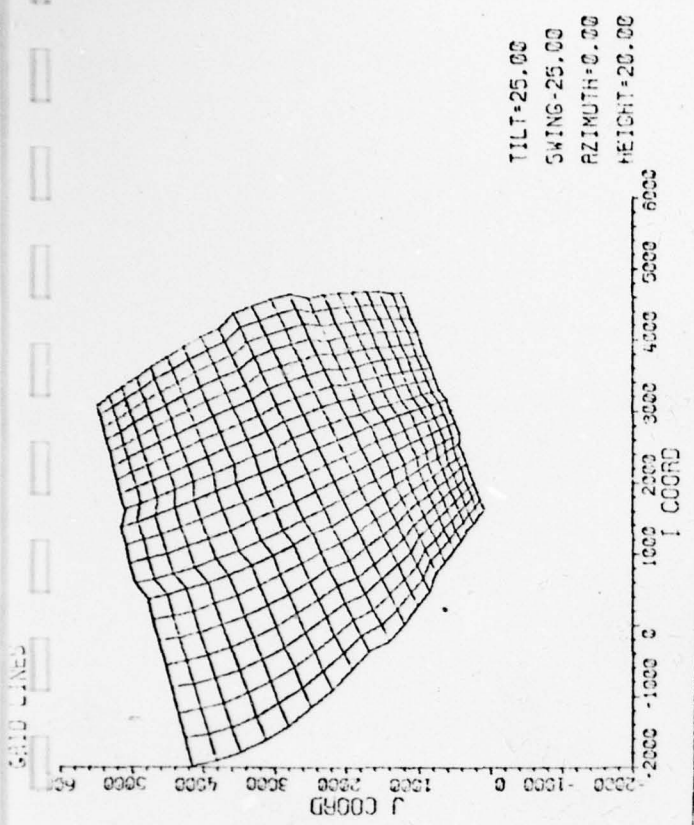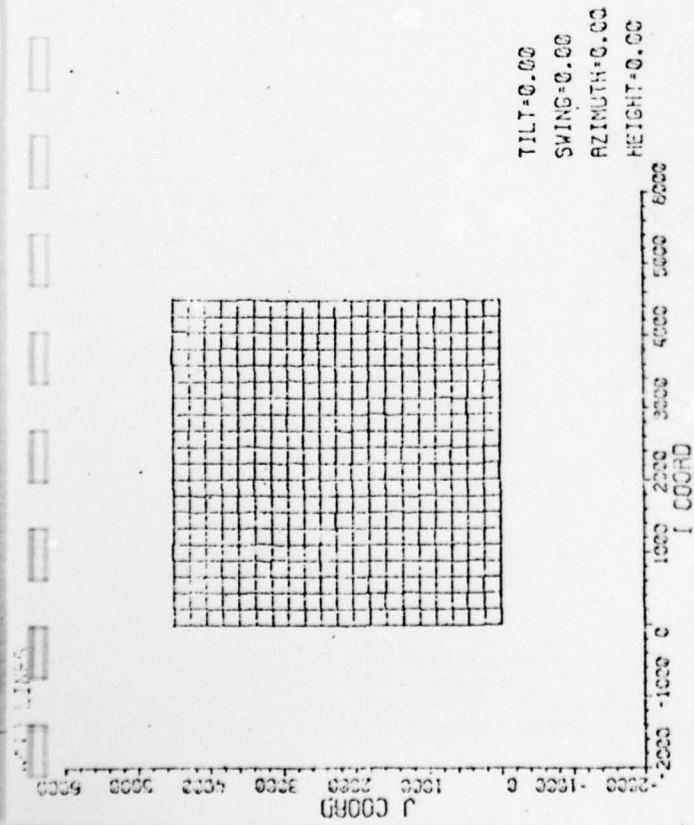
Figure 3.19   Panoramic Photography. 25° Tilt, 25° Swing
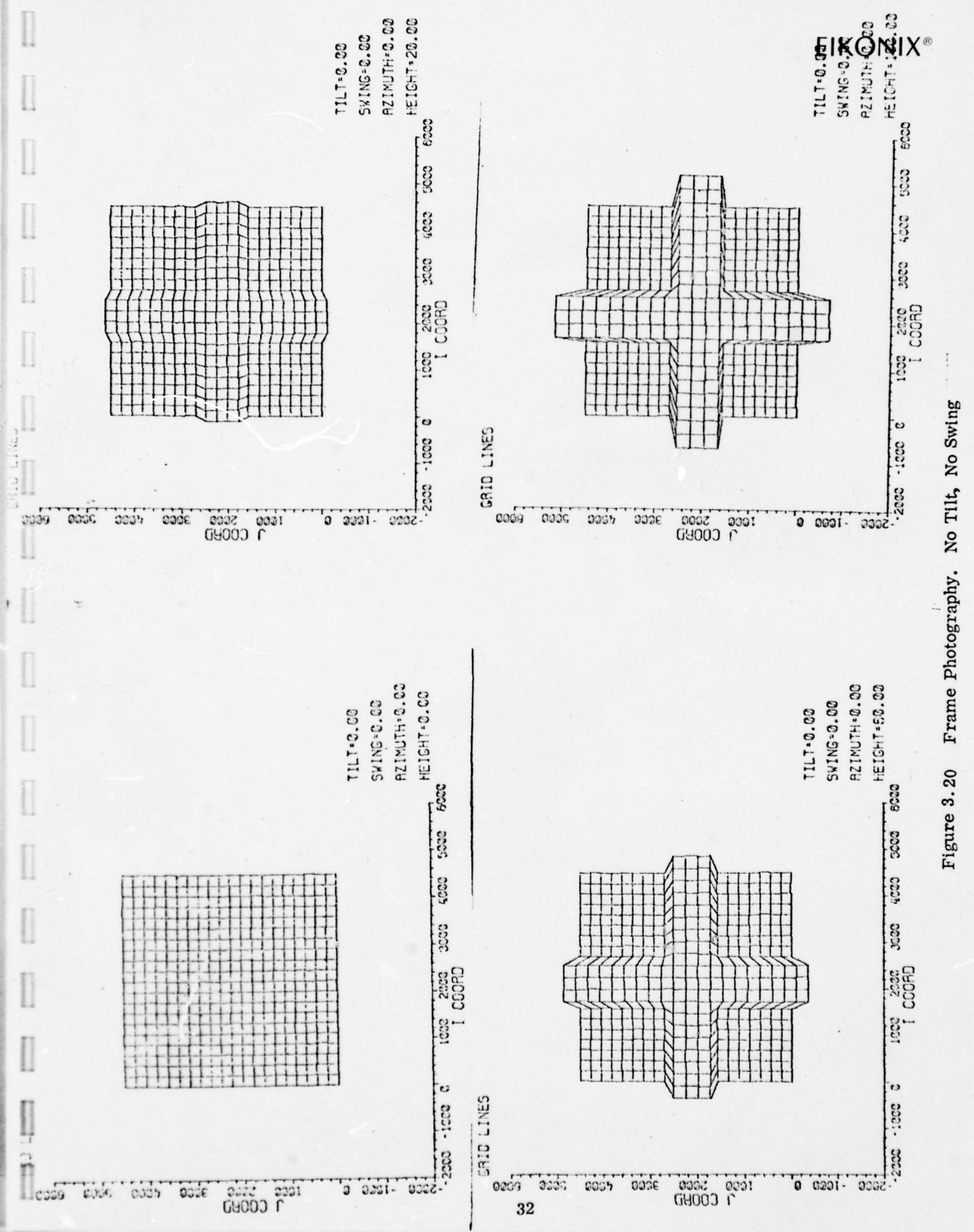
EIKONIX®

Figure 3.20 Frame Photography. No Tilt, No Swing

TILT=25.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=20.00

GRID LINES

TILT=25.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=100.00

GRID LINES

TILT=0.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=0.00

TILT=25.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=50.00

GRID LINES
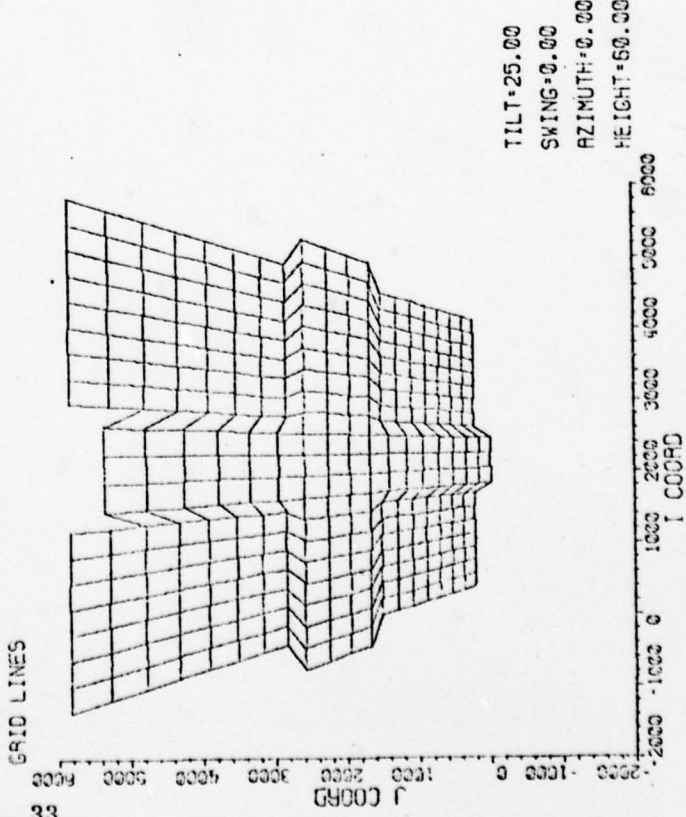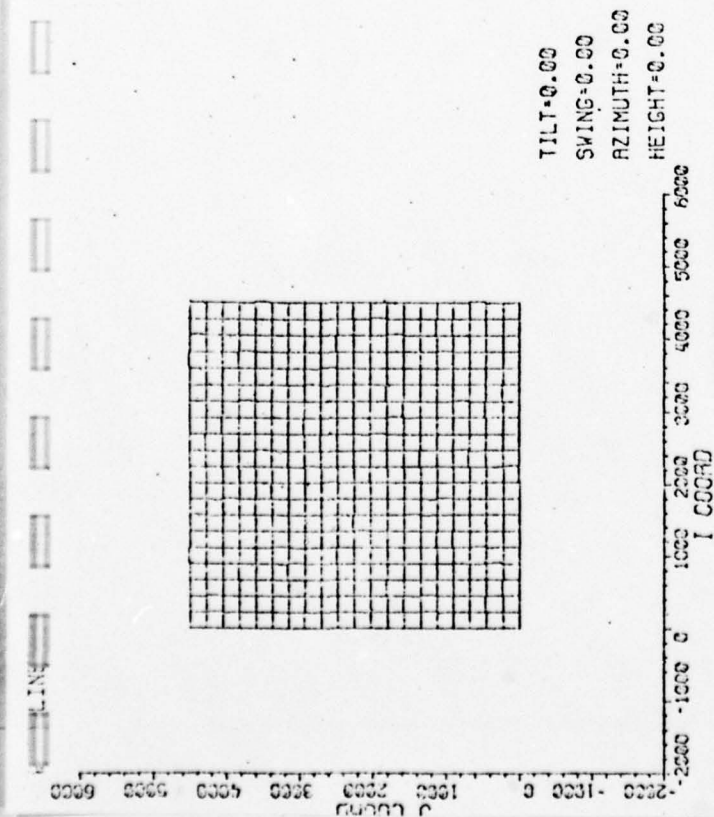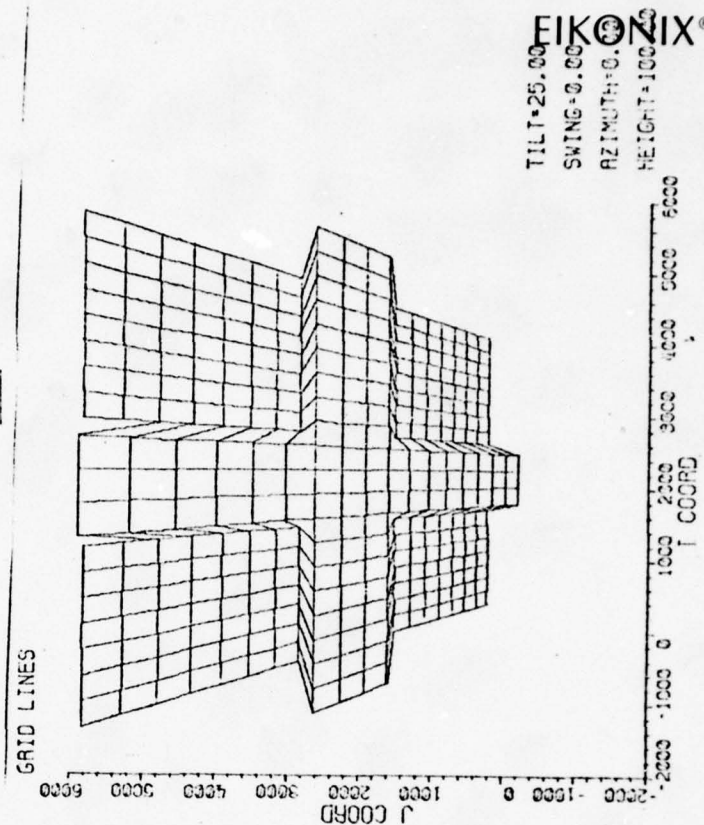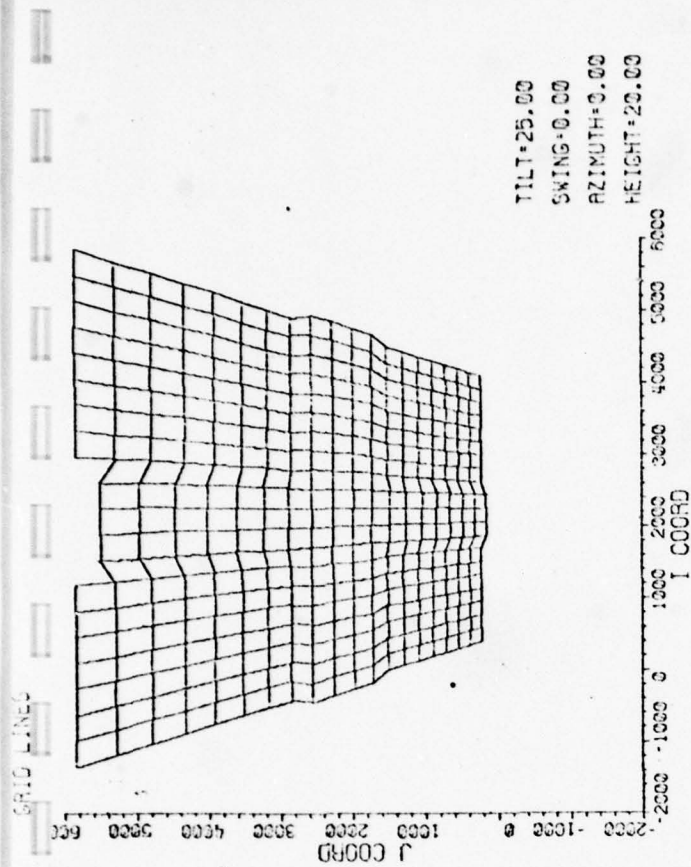
Figure 3.21 Frame Photography. 25° Tilt, No Swing
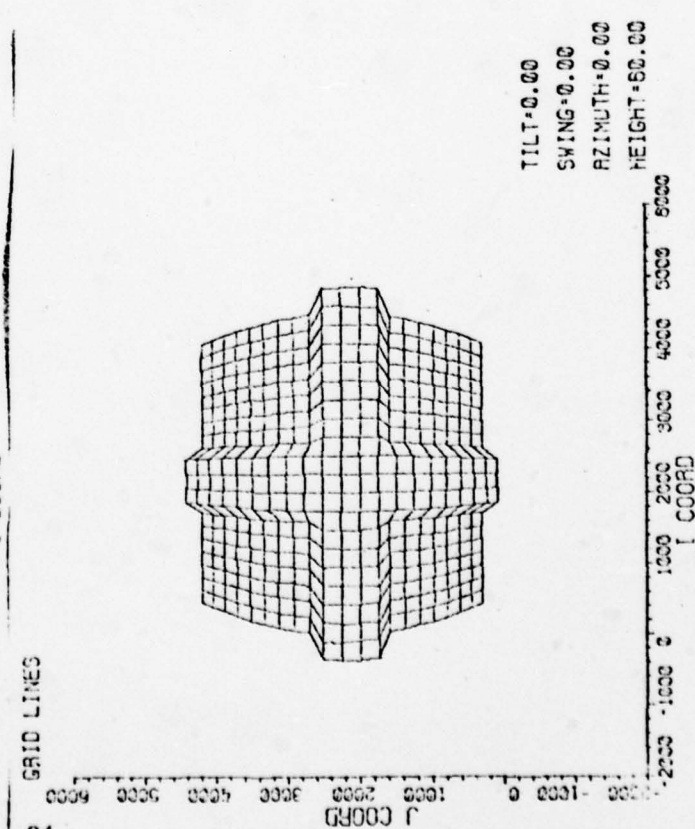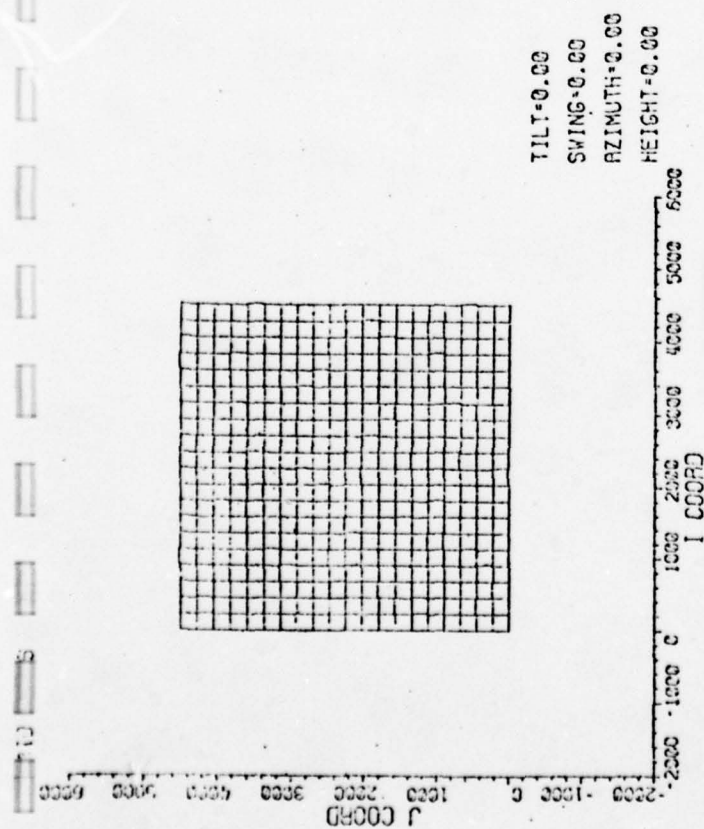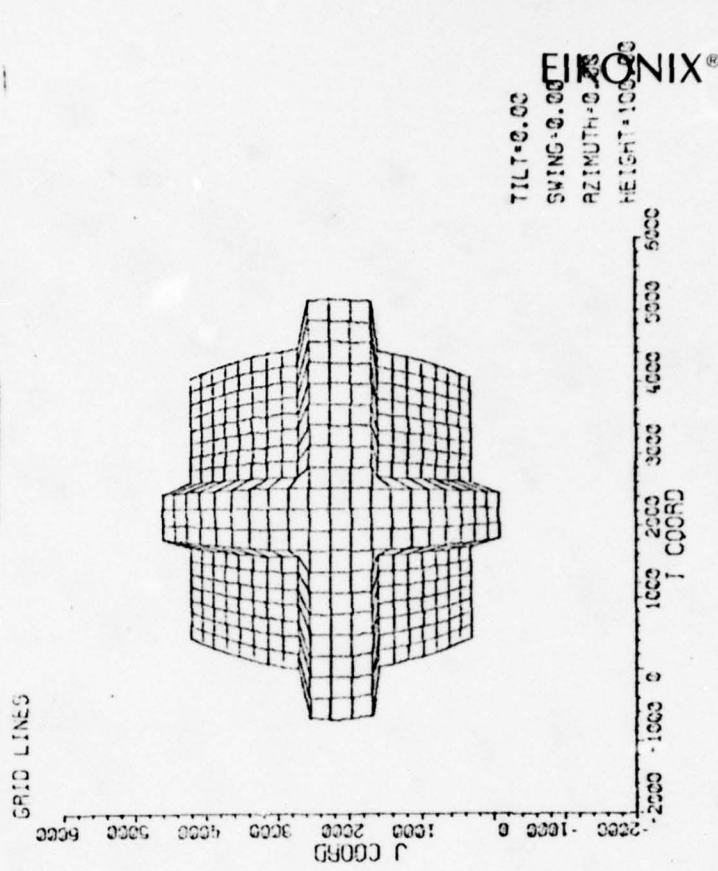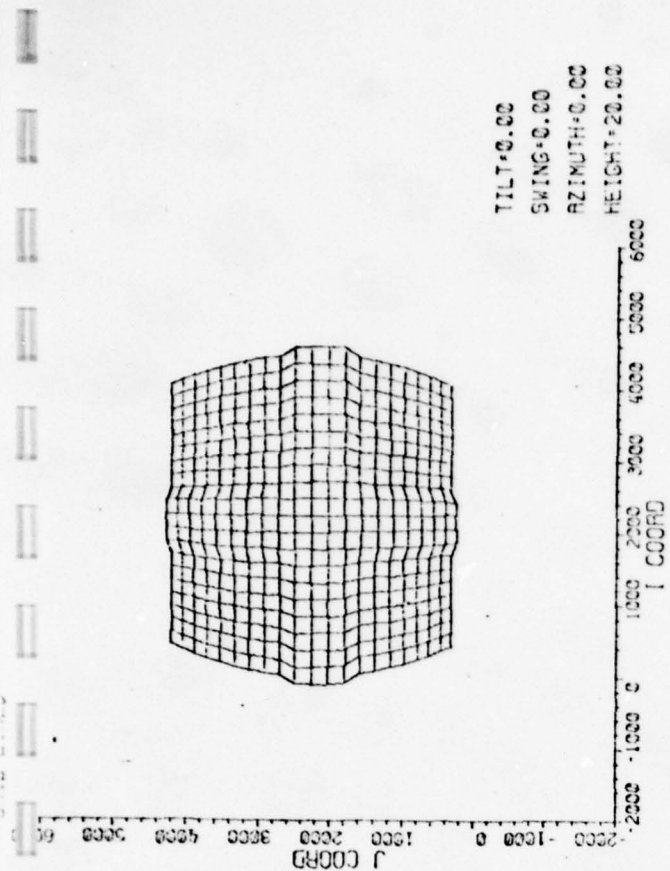
Figure 3.22   Panoramic Photography.   No Tilt, No Swing

TILT=25.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=20.00

TILT=25.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=100.00

TILT=0.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=0.00

TILT=25.00
SWING=0.00
AZIMUTH=0.00
HEIGHT=60.00
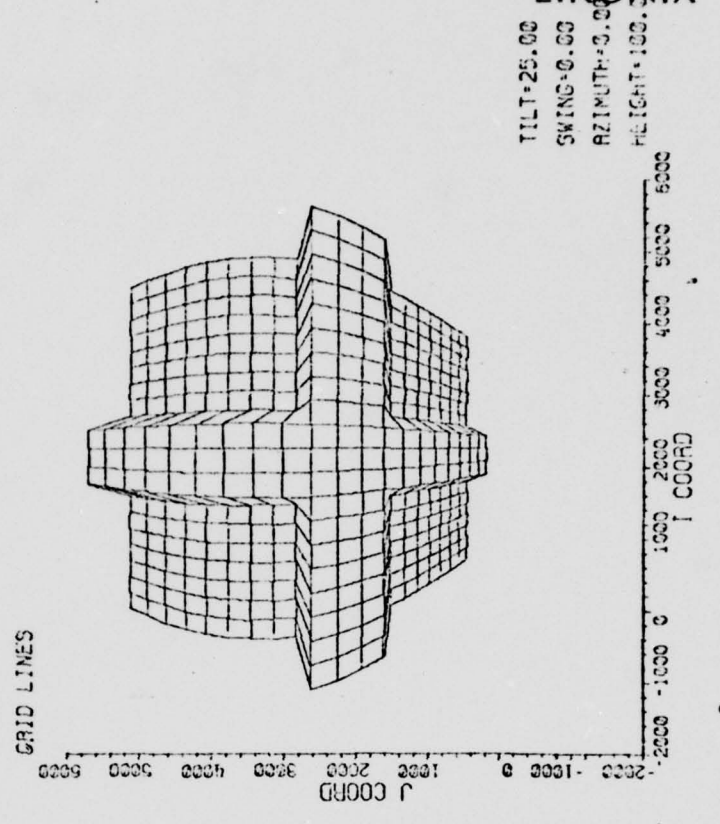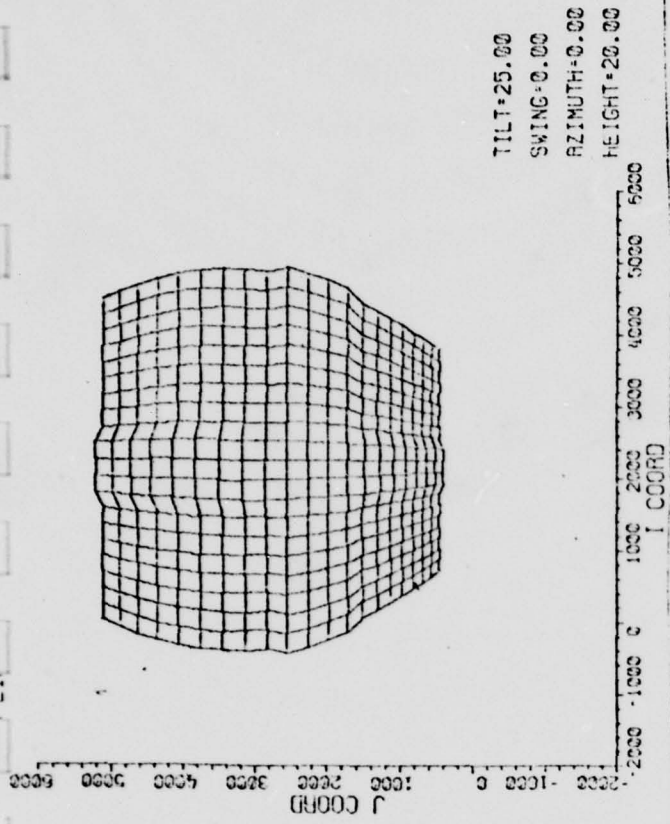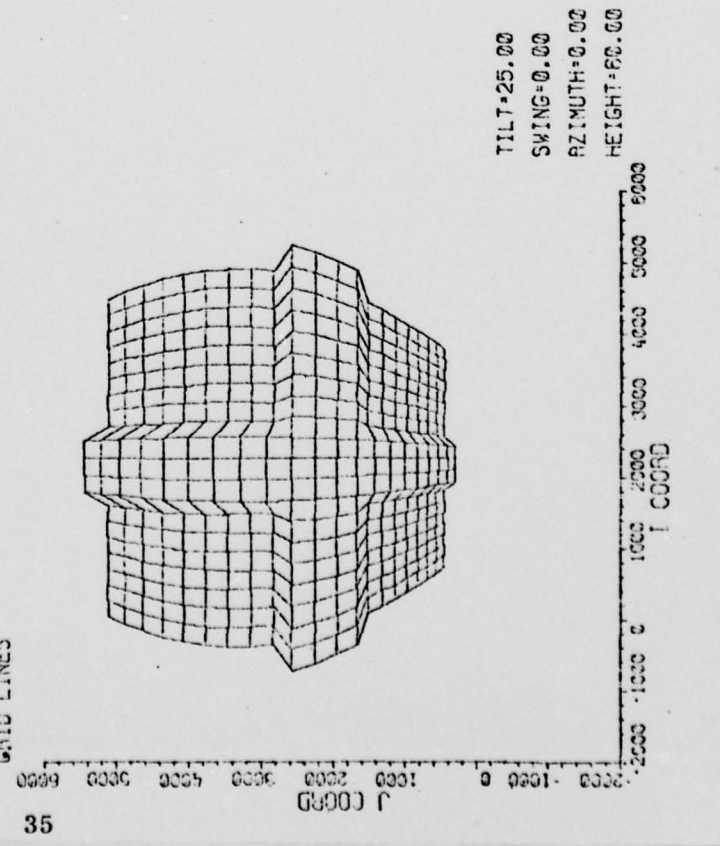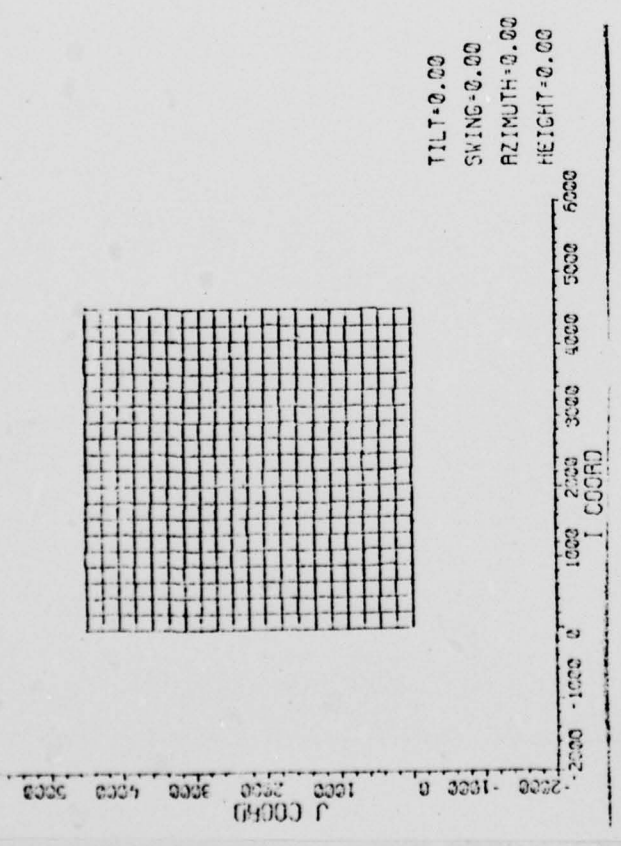
Figure 3.23 Panoramic Photography. 25° Tilt, No Swing

0° Tilt, 0° Swing, 0° Azimuth

30° Tilt, 0° Swing, 0° Azimuth

Figure 3.24   Simulation of Rectification Algorithm

3.5   Criteria for Assessment

Having reviewed existing equipment and analytical techniques, we have established the following criteria for assessing our system concept.

1. System portability – A van-mounted unit, in a non-optimum environment, should not contain elaborate opto-mechanical hardware which would be delicate and prone to maladjustment.

2. Insensitivity to camera attitudes – The time required to process the orthophoto should be insensitive to variations in camera orientation.   No limitations on camera orientation should be imposed other than the basic undersampling that exists for extreme angles and position.

3. Cosmetic appearance – The orthophoto should be sufficiently aesthetically pleasing, so as not to induce measurement errors.

4. Operator intervention – Since this equipment is to be operated under sub-optimal conditions, operator intervention must be kept to a minimum and critical steps must be avoided.

5. Flexibility in processing – The system concept should easily be adapted to additional digital image processing for such purposes as image enhancement.   Adaptation to changing orthophoto requirements and new camera types should be facilitated.

6. System longevity – Short–term future technological advances, such as increasing memory densities, should be easily incorporated to enhance system effectiveness and increase system longevity.

4   VAN ORTHOPRINTER SYSTEM CONCEPT

4.1   System Design Concept

In accordance with the orthoprinter assessment criteria we have established the following design concept. First, scanning of the input image and writing of the output picture would be accomplished on a drum scanner/writer. Selection of this unit was made on the criteria or ruggedness, availability, and reliability, as well as cosmetic appearance of the output. Second, the system controller, will be a PDP 11/34 type computer. This choice is made in order that the system contains sufficient processing power for changing image processing requirements. Six additional subsystems would connect to the 'computer bus'. This would give bi-directional access between the computer and all other system components. (Refer to Figure 4.1.) A tape unit and hardcopy terminal would serve for input of programs, digital terrain data and any other man/machine inputs. The hardcopy would also serve to document the process.

Completing the digital subsystem are three components, a micro-programmable computation unit, and two image memories. The computation unit, slaved to the controlling computer would, at high speed, perform the algorithmic transformations required. The transformation to be executed would be loaded in the micro-program position of this unit by the PDP-11 on initialization. Image memories 1 and 2 would serve to retain interim process information in order to accomplish the process described in Section 4.2. Two additional system busses, the 'computation' and 'scanner bus', would link these units (refer to Figure 4.1) in order to maintain system throughput. Finally, the actual digitization of film would require the image data collection system.

4.1.1   Rotating Drum Scanning/Writing System

A rotating drum type of scanner and recorder has been selected for this system for the following reasons: the mechanical simplicity of the rotary system as compared with conventional x-y translation system allow us the opportunity

TAPE UNIT

INPUT MEDIA FOR PROGRAMS AND TERRA[IN]

UNIBUS

SCA[NNER]

UNIBUS
INTERFACE

STEPPER
CONTROL

PIXEL/LINE
COUNTER

X-Y DECODE OF
DESIRED
PIXELS

S[C]
D[...]
IN[...]

DRUM ENCODER

ARRAY CONTROL

COMPARATOR

DRUM

4 ∅CLOCK   VAB   SOCEVN   SOCODD

CCPD   EVEN   EVEN A/D

ODD/EVEN
MUX

FIFO
256×8

MOTOR

ODD   ODD A/D

YSTAGE

STEPPER

SCANNER BUS

TERRAIN INFO

TERMINAL

SYSTEM KEYBOARD AND HARD COPY

PROCESSOR PDP 11/34 WITH

MEMORY
  FP11AU FLOATING POINT
  SERIAL INTERFACE
  PARALLEL INTERFACE

SYSTEM CONTROLLER

UNIBUS

SCANNER

SCANNER
BUS
INTERFACE

MEMORY 2

HIGH-SPEED
SORTER
16/1 µs

ADDRESS
COUNTER

X-COORD

Y-COORD

ORTHO-PHOTO

DENSITY

OUTPUT
COMPARATOR

MEMORY

Y COORDINATE

MEMORY
CONTROL

DIRECTORY

8k ×16

ADDRESS
COUNTER/
REGISTER A

R/W CONTROLS 2

2-TO-1 MUX

Y COORD
ALONG DRUM

X COORD
ACROSS DRUM

LINK POINTER

ORTHOPHOTO
COORD

BASIC RATE: 20 kHz IN, 1 MHz OUT

SEQUENCE OF EVENTS:
1. LOCATION POINTED TO BY DIRECTORY
   (Y-COORDINATE) = CURRENT ADDRESS
   (COUNTER).
2. LOCATION POINTED TO BY ADDRESS COUN
   X-COOR, Y-COOR, ORTHOPHOTO COOR.
3. DIRECTORY (Y-COORINATE) = ADDR COUN
4. AC = AC+1

SCANNER BUS

BUS SWITCH

2

WRITER BUFFER

MEMORY BUFFERS OUTPUT FOR PARALLEL PROCESSING

WRITER

MODIFIED OPTRONICS INTERNATIONAL INC.
PHOTOWRITE SYSTEM

TH 32-k MEMORY

UNIBUS

COMP

μ-CONTROL
MEMORY

SELECT

μ-SEQUENCER

4-1
MULTIPLEXER

SELECT

MULTIPLIER
8×8

ADDER
8 BIT

4-1 MUX

ADDER
48 BIT

DUAL-PORT
STACK

MULTIPLIER
8×8

ADDER
8 BIT

MULTIPLIER
8×8

48 BIT

EXPONENT 1

EXPONENT 1
REGISTER

ADD/SUBTRA

EXPONENT 2

EXPONENT 2
REGISTER

8 BIT

MEMORY
ESS

COUNTER=
OR.
COUNTER.

COMPUTATION BUS

3

RITER BUFFER

WRITER

MODIFIED OPTRONICS INTERNATIONAL INC.
PHOTOWRITE SYSTEM

MORY BUFFERS OUTPUT FOR PARALLEL PROCESSING

UNIBUS

COMPUTATION UNIT

SELECT

α-CONTROL
MEMORY

L-SEQUENCER

SELECT

α-1
MULTIPLEXER

MULTIPLIER
8×8

MULTIPLIER
8×8

MULTIPLIER
8×8

ADDER
8 BIT

ADDER
8 BIT

α-1 MUX

48 BIT

ADDER
48 BIT

DUAL-PORT
STACK

1

2

RESULT
SHIFTER

EXPONENT 1

EXPONENT 1
REGISTER

EXPONENT 2

EXPONENT 2
REGISTER

ADD/SUBTRACT

8 BIT

COMPUTATION BUS

5-17-78   EIKONIX   FIGURE 4.1   ORTHOPHOTO   SYSTEM 4

EIKONIX®
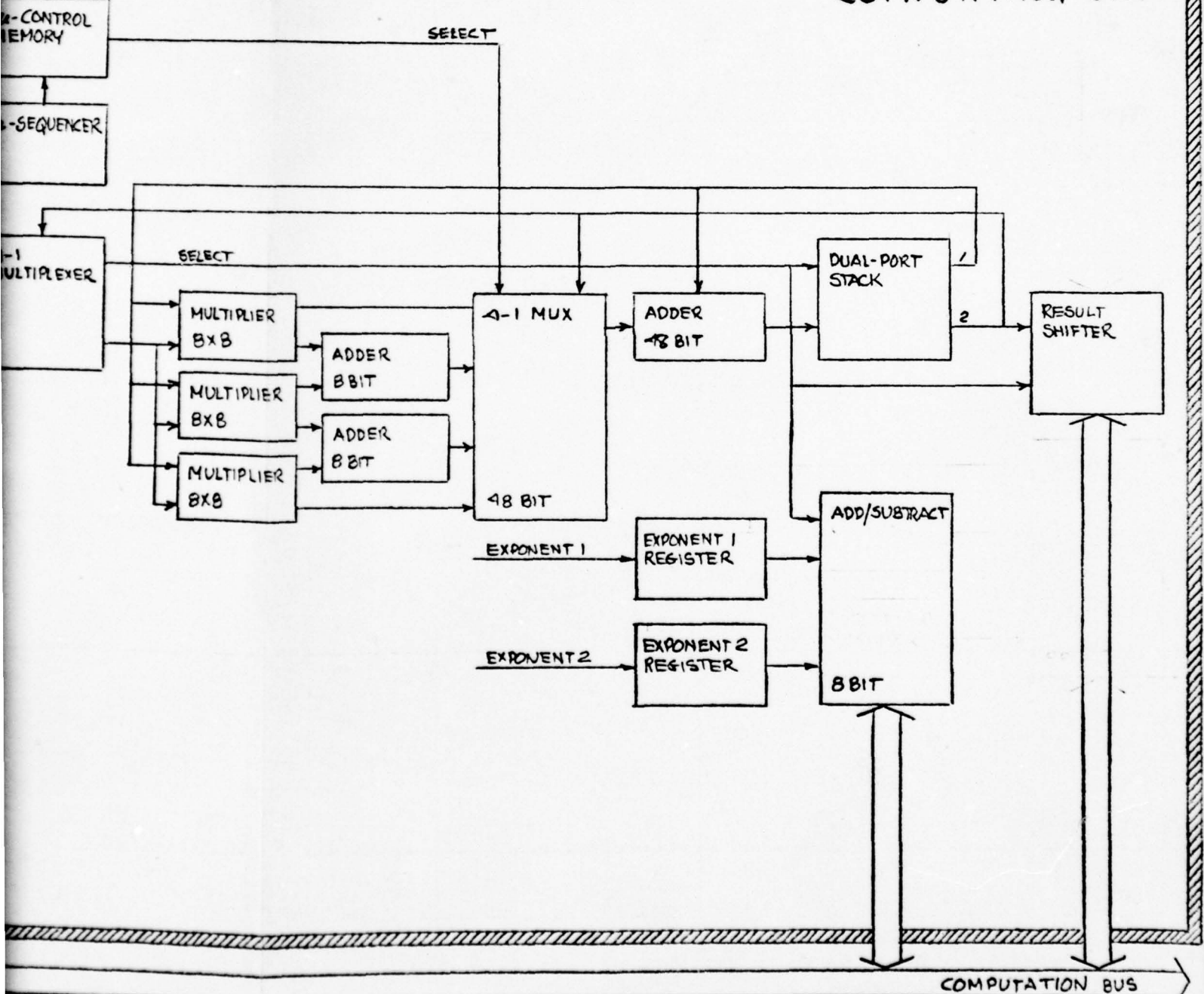
of providing the user with a more rugged, easily maintained, high degree of re-liability, and a more cost effective system. If needed, this rotary drum system can also provide greater scanning/writing speeds than the x-y system without incurring excessive stress or wear on the system.

At the data collection rates at which this system will operate, it is not possible to physically scan a single detector along the curved path necessary to collect data for a straight path scan on the orthophoto. We therefore propose that the conventional drum scanning collection system be modified to include a linear array of silicon diodes, all optically coupled to the input imagery so that each diode collects the illumination passing through a 25μm square to 50μm square area of the film. The linear diode array would consist of 1024 to 1728 diodes placed in a row such that for a single rotation of the drum a 6 to 8 cm stripe is scanned on the input film. After each scan, and during the dead space before the leading edge of the input photograph comes around to the sensor, the sensor assembly can be axially moved to a new read position. The motion of the scan head would be via a drive screw and under computer control.

Since the physical shape of the diode elements are square and the data acquired from these diodes is from an image that is moving during acquisition time, it may be necessary to couple the array to the imagery through an anamorphic optical system, so that the shape of the instantaneous sampling spot on the film is not square but rectangular. By controlling the aspect ratio of the diodes, with the short dimension in the rotational direction, the effective resolution along the scan direction can be controlled for best resolution. The effective film sample shape in the scan direction is a function of the diode shape and the smear shape due to integration time and film velocity.

An alternative to the anamorphic optical approach is a diode averaging method whereby two neighboring diodes can be averaged as a single pixel sample. This provides a 2:1 aspect ratio.

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Once the drum scanning/writing approach was chosen as a best potential solution to a field hardened van-mounted orthoprinter system, we met with Optronics International to discuss the feasibility of the design and the possibility of adapting one of their scanner/writer systems for this application. From this discussion it was felt that the van installation was no problem provided some mechanisms within the drum scanner/writer would be ruggedized for this environment. An Optronics Drum System is shown in Figure 4.2. The modification of the sensing element is feasible. In fact, some available drum systems now use multiple read/write arrays. To check pixel registration capabilities in both the circumferential and axial directions, we digitized and recorded a portion of an aerial photograph using a drum scanner. The results were extremely favorable. The pixel element for this image was 50μm square and the pixels were registered with respect to one another to better than 5μm. With this registration accuracy capability, the drum scanning/writing system should satisfy the requirements for a field hardened van-mounted off-line orthoprinting system.
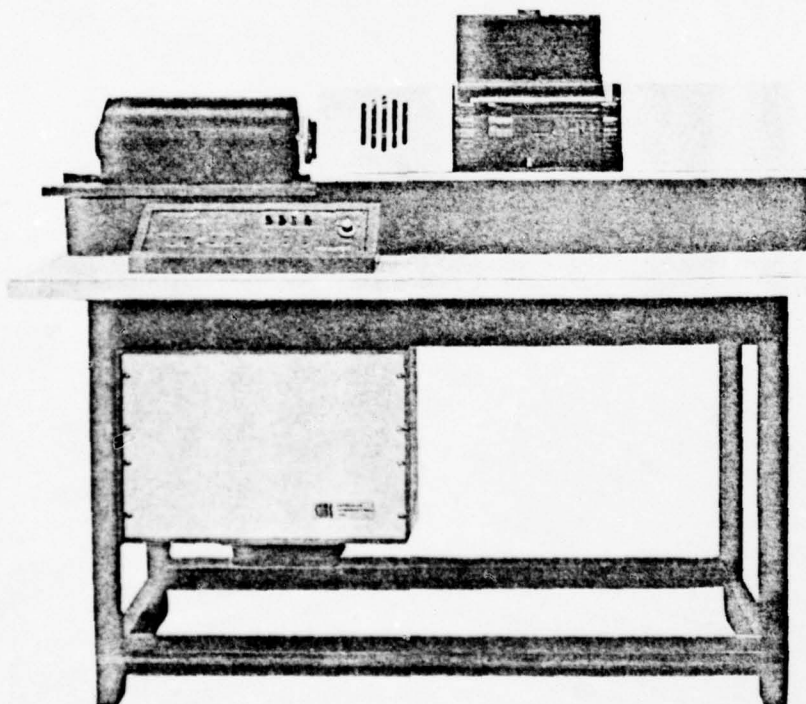
Figure 4.2 Optronics Scanner/Writer System

Commercially available drum scanners can be modified to obtain field hardened operational systems. The drum scanner/write system will be mechanically hardened such that the alignment of the scanning and write heads will be maintained during transport. Other areas of the drum system to be strengthened include the film enclosure, the lamp house, and fiber optics assembly, and the electronic rack assembly.

Position control of the drum scan head would be via a stepping motor driving the lead screw. The reference for the stepper driver system would be derived from the home position of the scan head. At the home position, the location of the scan head will be determined coarsely by a switch contacting the carriage. The fine position determination will then be via an optical detector and rotating disk in the drive screw. The angular position of the drum will be determined by a rotational shaft encoder capable of angular resolution to 20 arc seconds. The rotational speed of the system will be 10-20 revolutions per minute requiring positional data from the shaft encoder at a rate of 16 kHz.

Initialization of the input photo to the drum scanner reference system can be accomplished by manually aligning (i.e., operator movement of the drum and sensor) four fiducial marks under the read sensor and inputting this coordinate information into the computation system. Operator viewing optics would be provided at the scan sensor. If control point data is required from the input photo, the operator would continue in the same fashion, by manual rotation of the drum and translation of the read sensor to each control point. During a preview mode (on an auxiliary table) the input imagery can be examined for the location of control points. These positions on the film can be marked at this time so that these points can readily be found when the film has been mounted on the drum. The particular technique for marking has not been specified, however some of the conventional film markers now in use may be acceptable.

4.1.2   Digital Processing Hardware

4.1.2.1 Minicomputer and Peripherals

A PDP 11/34 minicomputer with 32K memory, FP11-AU floating point processor and interfaces would serve as the controlling unit. At the beginning of the orthophoto process, information relevant to the process such as camera attitudes, would be input on the system terminal. The Digital Terrain Model would be fed into the system via the tape unit. In an interactive manner the operator would guide the computer-controlled scanner to the fiducials or control points in order that the computer could register the input image. The PDP 11/34 would then perform all mensuration required to compute the coordinates of the orthoprinter transformation. The PDP 11/34 would then set up all other system units to commence the orthoprinting process.

During the actual orthophoto process the 11/34 would serve to control data transfers between subsystems and synchronize the parallel processes. It would also, when required, assist with the transformation and the list re-ordering process. In addition, the PDP 11/34 would perform local image enhancement by smoothing gray levels on a local basis if this proved desirable. The PDP 11/34 would not be capable of performing the actual tranformation due to speed limitations. This requires a computation unit which can handle the throughput.

4.1.2.2 Computation Unit (See Figure 4.1)

All transformations and interpolations will be computed by the computation unit subsystem. It will consist of a micro-sequencer which controls hardware artihmetic logic and a small results and constants memory stack. During the initialization of the orthophoto process, the 11/34 would load the results and constants stack with the coefficients of transformation. The micro-sequencer would also be loaded with the order of computation. Once initialized, the micro-sequencer would be capable of iteratively stepping over the orthophoto pixel values

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and computing the required input image coordinates. It would seek terrain data from the 11/34 as it was required. The hardware arithmetic logic would operate at sufficient speed to compute one transformation in less than 50 microseconds. Several of these computation units can be paralleled for future system enhancement.

As each x, y coordinate pair was computed, the x, y values would be transmitted over the 'computation bus' to image memory 1.

4.1.2.3 Image Memory 1 (See Figure 4.1)

Image memory 1 would serve as storage medium for the list of 72,000 points as they are computed by the computation unit. They would be stored in orthophoto order, but would contain linking information which would assist in reordering them in scan sequence. The memory would have a directory representing segments of the input image. This directory would link all coordinate pairs within an image segment, when this list is later transferred to image memory 2. The linking will serve to minimize the reordering process. This memory will be approximately 72,000 words of 60 bits each.

4.1.2.4 Image Memory 2 (See Figure 4.1)

As each N lines of orthophoto data are completely processed a data transfer will occur between image memory 1 and 2. As the data transfer occurs it will be reordered by a combination of the directory in image memory 1 and hardware ordering logic in image memory 2. In some cases, where the reordering task is too large for this hardware, the PDP 11/34 will assist.

During the scanning process the coordinates in image memory 2 will be sequentially loaded with the digitized pixels as they occur beneath the scanning diodes. This transfer occurs over the scanner bus. Between scans, these density values will be transmitted to the output buffer memory. Image memory 2 capacity is approximately 72,000 x 60 bits.

4.1.2.5 Output Buffer Memory

This is a 72,000 byte memory serving to buffer the ortho-photo output writer in order that writing can be accomplished at a steady velocity. This buffer could serve to be a work area for further digital enhancement of the output image.

4.1.3   Image Data Collection System

This section details the EIKONIX approach to implement a high speed image data collection system, required for the off-line orthoprinter.

Off-line digital orthoprinter data processing requirements indicate that a conditional random access to film density data be made available. Since it is impractical to digitize the entire 4,500 by 4,500 pixels at $50\mu m$ sampling rate input format, and store data values in memory, the film itself is used as mass storage, and accessed for data as the processing algorithms and hardware dictate. In general, the important requirements are:

1. Limited random access data acquisition capability of density values relating to any point over 4,500 x 4,500 resolution element input format.

2. Resolution element on film equal to a $50\mu m$ x $50\mu m$ area.

3. Data rate of 10^5 points per second. (From design objective of 3 in^2/min.)

4. Density resolution of 0.1 minimum over a range of 1.7.

5. Hardware realization of desired requirements capable of withstanding specific transportation stress and related environmental conditions.

6. Moderate power consumption to accommodate limited source of primary power.

7. Conservative design practices that insure a high mean time between failure and obviate the need for frequent service and alignment.

4.1.3.1 Image Sensor - General

Various self-scanned photodiode arrays are presently available from several manufacturers. The array best-suited for this collection system task is a 1,024 element charge coupled photodiode array (CCPD) manufactured by Reticon Corporation. This array provides the best trade-offs between optimum sensor characteristics, lowest noise readout, and anti-blooming. The sensing elements are a row of p-n junction photodiodes spaced on 16μm centers and inter-digitated into a sensing aperture 16μm wide.

4.1.3.2 Theory of Operations

Light incident upon the sensing diodes generates a photo current which is integrated and stored as a charge on the capacitance of each of the photo diodes. If the charge accumulated on any one diode exceeds a saturation value, the excess is shunted to ground through an anti-blooming gate. At the end of each integration period, the charges on all the diodes are simultaneously switched through transfer gates into one of two analog CCD shift registers. The odd diodes are switched into one register and the even diodes into another. Immediately after this transfer a new integration period begins. Readout is accomplished by clocking the CCD shift registers so that the charge packets are delivered sequentially into two charge detection circuits. The registers deliver the charge packets alternately, allowing the inactive charge detector to be reset to a fixed value while the alternate detector is active. The two signals then may be processed independently and provide a means to allow longer analog-to digital conversion times, by digitizing first the even, and, then the odd diode data in two independent analog-to-digital converters. The digital data is then demultiplexed to one channel of 8 bit data.

4.1.3.3 Array Control Logic

The array control logic generates the four phase of clocks to operate the CCD. The integration time is precisely controlled using a crystal

generated clock controlling the V_{AB} line to the CCPD. Velocity variations of the drum are compensated for by triggering the integration time from the drum encoder (See Figure 4.1). The two Start of Converts (SOC EVN and SOC ODD) are generated to control the analog-to-digital converters.

4.1.3.4 A/D Converters

The two medium speed Analgo-to-Digital Converters have conversion times of $1.5\mu m$ seconds. Each converter operates one of the analog output channels of the CCPD array. The 8 bit data results are transmitted to the ODD/EVN multiplexer.

4.1.3.5 Pixel/Line Counter

The Pixel/Line Counters generate the x, y coordinate for the data points being generated by the CCPD. The reference offset is added to the CCPD pixel count to generate the x coordinate. A 4,500 position line counter generates the y corrdinate using the Start of Line and Drum reference signals from the drum encoder.

4.1.3.6 x-y Decode of Desired Pixels

Hardwire high speed logic decodes the x', y' address of the desired pixels. The x', y' address is compared to the current coordinate of the scanning logic until the required pixel is collected. The desired pixel is strobed into the FIFO to await transfer to the scanner bus.

4.1.3.7 ODD/EVN Mux and FIFO

The ODD/EVN Multiplexer sequences the output of the two A/D's into the First In First Out buffer. The selected pixels are stacked in the FIFO allowing block transfer of data from the Collection Scanner to the Scanner bus.

4.1.3.8 Stepper Control

The stepper control logic controls the y offset of the CCPD from the reference y position. The stepper control receives commands from the main processor through the Unibus Interface. A Reference Offset binary counter generates the y position of the first diode of the CCPD.

4.1.3.9 Scanner Bus Interface

The Collection Unit transfers all data through the Scanner Bus Interface, with controls for interfacing to the other devices on the interface bus.

4.1.3.10 Unibus Interface

The Unibus Interface connects the scanner with the main processor. Command and status for the stepper control are transmitted through this board.

4.2 Process Discussion

Inherent in the hardware discussion is the objective of minimizing the operator intervention that is required. The primary functions of the operator occur in setting up the input image for the current orthophoto.

4.2.1 Orthoprinter Process – Set-Up (Refer to Figure 4.3)

The first tasks of the operator are to provide the computer with information relevant to the process. This includes input of the DTM data as well as input through the system terminal of camera exterior orientation parameters (if they are known). Secondly, the operator must mount the input film on the drum after clamping it to the platen.

At this point in the initialization process, two distinct cases emerge. Case 1 is a simple case of a frame camera with known attitudes. The requirement on the operator in this case is to coarsely locate the scanning array over the fiducial marks (one at a time) and inform the computer as he has done so. This would

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MOUNT IMAGE ON PLATEN
MOUNT PLATEN ON SCANNER DRUM

LOAD DIGITAL TERRAIN MODEL
INTO COMPUTER USING TAPE UNIT

INPUT CAMERA ATTITUDES (IF
KNOWN) AND OTHER CONTROL
INFORMATION

CASE 1

FRAME CAMERA WITH
KNOWN ATTITUDES

LOCATE FIDUCIALS
UNDER SCANNER AND
NOTIFY COMPUTER
THROUGH TERMINAL

CASE 2

PAN CAMERA OR FRAME
CAMERA WITH UNKNOWN
ATTITUDES

PRECISELY LOCATE
CONTROL POINTS AND INPUT
COORDINATES TO COMPUTER

CRITICAL STEP

OPERATOR
INTERVENTION

CONTROLLING COMPUTER:

1) COMPUTES COEFFICIENTS OF TRANSFORMATION

2) DETERMINES BOUNDARIES OF ORTHOPHOTO

3) SETS UP OTHER SYSTEM UNITS TO COMMENCE
   PROCESS

Figure 4.3 Initialization of Orthophoto Process

be done in an interactive manner with the computer validating the fiducial. Case 2 would require the operator to precisely locate a number of control points using a viewing graticule provided on the drum. This would be necessary if a PAN or a frame camera with unknown attitude was used.

After the operator has completed input of fiducials or control points, the controlling computer will compute the limits of the output ortho-photo in such a way as to produce a rectangular output image. (Refer to Figure 4.4.) It will also compute the coefficients of transformation and transmit them to the microprogrammed computation unit.

4.2.2   Orthoprinter Process – Scanning and Writing
(Refer to Figure 4.5)

After a brief starting time during which the orthophoto 'pipeline' is filled, the process consists of three parallel processes, coinciding with 1 revolution of the scanning drum. They consist of:

(1) The computation unit would compute a list of input drum coordinates for those density values currently required by the orthophoto. This would be done for N* lines of the orthophoto at a time. This list would be stored in Image Memory 1 in order of orthophoto occurrence. Also, in order to facilitate the reordering of this list in scan sequence at a later point, linking information would also be stored in Image Memory 1.

(2) Image Memory 2, which contains the previously computed list of desired input image pixels, would be loaded with the densities of those pixels as they come under the scanner. The list in Image Memory 2 has been reordered in scan sequence to facilitate this process.

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*N Initially would be 16
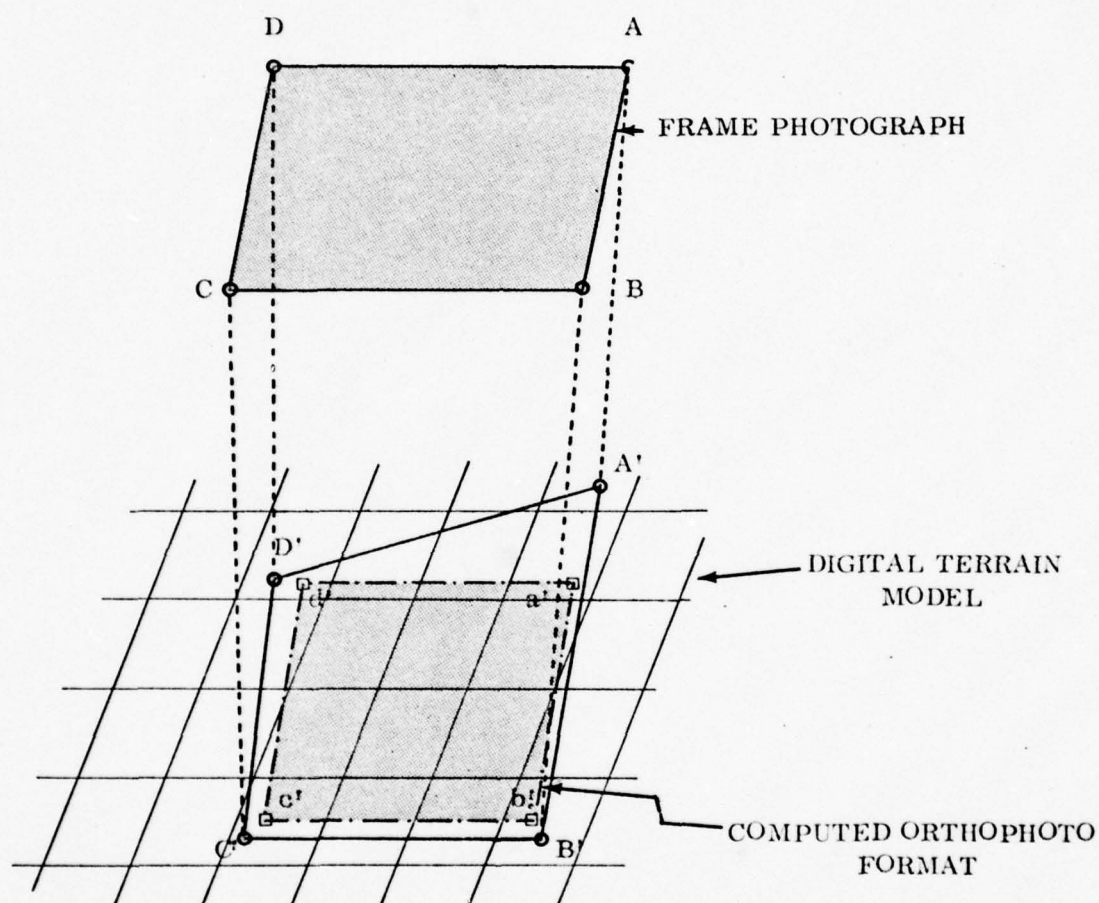
Figure 4.4   Determination of a Rectangular Orthophoto
Format from a Frame Photograph

INITIALIZE

Computation unit computes a list of
input image coordinates for N lines
of the orthophoto and places list in
image memory 1.

Transfer image memory 1 contents
to image memory 2, re-ordering the
list from orthophoto sequence
to scanner sequence.

Computation unit computes a list
of input coordinates for N lines
of the orthophoto and places list
in image memory 1.

Image memory 2 is compared against
location of scanner. As each location
in image memory 2 is matched against
the scanner location, the desired density
is scanned and saved in image memory
2. One revolution of the drum will
typically provide all required densities
for 16 parallel lines.

A

Figure 4.5 Orthoprinter Process,
Initialization and Start-Up

A

Transfer density values obtained on last scan revolution to output buffer memory to be printed on orthophoto

Transfer image memory 1 contents to image memory 2, re-ordering the list from orthophoto sequence to scanner sequence.

Computation unit computes a list of input image coordinates for N lines of the orthophoto and places list in imagememory 1.

Image memory 2 is compared against location of scanner. As each location in image memory 2 is matched against the scanner location, the desired density is scanned and saved in image memory 2. One revolution of the drum will typically provide all required densities.

Print N lines of orthophoto as density values contained in the output buffer memory.

ORTHOPHOTO COMPLETE — NO → A

YES

DONE

Figure 4.5 Continued, Primary Orthoprinter Processing

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(3) The output writer would print the previously obtained density values as N lines of orthophoto.

In between each drum scan, two events would occur. First, the density values loaded in Image Memory 2 during the last revolution would be transferred to the output buffer memory. Second, the list of coordinates stored in Image Memory 1 will be transferred to Image Memory 2. During this transfer the list will be reordered into scan sequence. In addition, during these transfers the diode array will be moved across the drum into position for the next drum revolution.

Basically, the process may be viewed as follows, with respect to the output orthophoto. (See Figure 4.6)

Orthophoto

Output Writing	N, Process 3
Scanning to Obtain Density	N, Process 2
Computation of Input Coordinate	N, Process 1
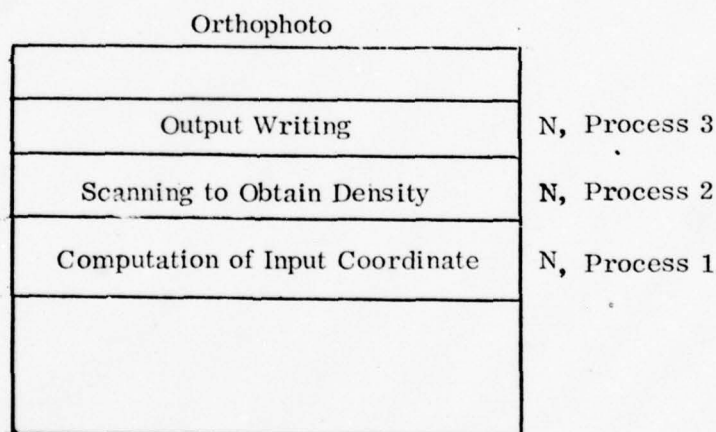
Figure 4.6 Orthophoto Pipeline Processing

Parallel processes 1, 2, and 3 lag each other by one segment of N lines. This parallelism is necessary to obtain high-speed throughput of large formats. It should be noted that in some cases, several revolutions of the scanner drum will be required to obtain all the density values called out in the list. This would only occur, however, in extreme cases where pixel shifts of greater than 500 occurred.

4.3   Spot Shaping for Image Smoothing

Raster scanned imagery that would be the output product of the off-line digital orthoprinter, can be smoothed so that raster lines do not reduce the aesthetic quality of the orthoprint. Spot smoothing is a technique that has been developed and tested. Appendix B presents a full description of the definition of spot shaping and means for its implementation in system optics. An example of smoothed imagery by this technique is given.

4.4   Design Conclusions and Estimated Throughput

The Orthoprinter system, outlined above, utilizes a combination of high speed two-dimensional access to the input image, coupled with a flexible digital unit in order to meet the stated performance goals. This design concept represents a flexible unit, easily adaptable to additional processing requirements or changing orthophoto requirements. Operator intervention and expertise is minimized by placing most critical steps under control of the computer. All of the system components, included in this design, may be van-mounted and require a minimum of calibration.

A timing analysis is presented here to provide an estimate of the throughput of the digital orthoprinter. The key system element that defines data throughput is the amount of memory used. The design approach given here enables 16 parallel lines of data output for the drum writer.

Drum rotation would occur once per six (6) seconds. During each rotation, 16 scan lines would be processed. At a 50μm sample increment this yields 0.031". Therefore, a processing rate of 2.84 in^2/min is obtained.

Processing rate is inversely related to memory size. To increase processing rate by a factor of 2 or 4 is possible by doubling or quadrupling the memory size used in image memories 1 and 2 because the other system components have a factor of 2 to 4 additional throughput capacity. This is totally a cost issue, as the additional memory would have minimal impact on system bulk.

The limiting time factor in the current design is the search and digitization of the desired pixels for the orthophoto. For the nominal drum speed of 1 revolution per 6 seconds, (assuming 9" format and 16 lines per revolution), 72,000 pixels must be computed. This requires that the computation unit operate at a speed of 72,000 pixels per 6 seconds or approximately 83 microseconds/ computation. The intended computation unit would operate on a micro-cycle of 100 nanoseconds and require one cycle for an add or a subtract and 4 cycles for a multiply. Therefore, it can perform 830 micro-cycles per pixel. The number of actual multiplications and additions required by the algorithm is closer to 100-150. Therefore, the computation unit could handle 2 to 4 times the through-put. In addition, further speed could be accomplished by adding in a second compu-tation unit to parallel the first. This is the reason for the statement that processing rate is inversely proportional to memory size (for a factor of 2 to 4) since, no other system components are closer to limiting throughput.

4.5   System Background

EIKONIX has extensive experience in interfacing linear diode arrays in data collection systems. We are now assembling four Automatic Edge Matching Systems (AEMS) after successfully developing the first system demonstrating its utility over the older VEM system. The AEMS employs a self-scanned 128 element linear array that collects edge profile data which is then processed by a DEC computer to produce a measure of edge width and contrast.

We have also employed linear diode arrays in two-dimensional image digitizing systems which are currently in various stages of development. One system using a 512 element linear array, has been operational for several months and provides EIKONIX with a digitizing capability necessary to carry out some of its imagery evaluation contractual commitments. The other digitizing system, using a 1024 element linear array is now being delivered to the Government as a component of a Text Restoration System. These design approaches to image digitization are proven and can provide for a compact, reliable and rugged field unit for film scanning.

5   RECOMMENDATIONS

This study program demonstrates the feasibility of the off-line digital ortho-printer for use in a field environment. A design approach has been defined that provides a means to develop the orthoprinter using commercially available hardware components. No new developments are required and fabrication can be performed at low risk with proven instrumentation. This study demonstrates that the system is feasible both in operating capability as well as development capability. Total throughput can be at the objectives initially cited (approximately 3 in^2/min) and the system can be designed with growth capability and flexibility to handle photographs from a variety of camera systems.

This study provides an approach that should be continued for development of a complete system design and system operating specifications. The following items are recommended steps that should be taken to achieve this design position, and are a requirement that leads to fabrication of a prototype field unit. The recommended follow-on program is as follows:

1. Definition of operational requirements.

The orthoprinter will operate with a stereo image and digital terrain data from stereo compilation equipment. The parameters of camera systems and the compiler, as well as fiducial and control point conditions, must be defined to enable a system design that has capability with present cameras and growth potential for future camera parameters.

2. Digital Orthoprinter Design

A detailed design of the digital orthoprinter is required to bring it to a level where the system is specified and costed for prototype fabrication. The design approach described in this report demonstrates that a practical configuration in cost and performance can be obtained.

3. Subsystem level testing

Several subsystems can be tested during the design program.
Rectification and differential rectification algorithms
can be applied to aerial imagery using sampling conditions
of the digital orthoprinter and digital terrain data tape.
Orthoprints of the aerial scenes can be generated on an
LBR and the aesthetic and information value of the process
demonstrated.

4. Operating system protocol

The operating procedures of the system can be defined in a
design program. This includes initialization and operation
to a product output.

The recommended design program will provide the Customer with system design
and specifications, system costs, defined algirithms, examples of scanned output
orthoprints, and procedures for system operation. This will provide full information
for fabrication of a prototype off-line digital orthoprinter for van mounted operation.

APPENDIX A

ORTHOPHOTO EQUIPMENT DATA

This Appendix contains data pertaining to most of the commercially available orthophotographic hardware. It has been obtained from either the literature or from manufacturers specification sheets.

SYSTEM:

Gestalt Photo Mapper II

Operation Mode:

On-Line

Scan: Patch method of printing with electronic correlation rectified area is 9 x 8 mm*

Speeds: variable depending on terrain

Z Range: Not available

Input: Extremely flexible although literature does not give specific limitations

9" x 9" input photos

Output: 20 x 25 cm with digital terrain model on magnetic tape

Capacity: Single model in 1.5 hours

Slope Correction: Equivalent to a 50th order polynomial

Remarks: A breakthrough in electronic image correlation makes this one of the most advanced machines available

* Proceedings, DTM Symposium, St. Louis, Missouri, May 8-11, 1978.

SYSTEM:

ZEIS GZ1

Operation Mode:

On-Line – connected to screw driven stereoplotters

Off-Line – stored profiles on SG-1 storage unit (can be edited)

Scan:	Y direction, slit sizes, 1mm x 2, 4, 8mm
Speeds:	2, 5, 3.3. 3.8, 5.0, 7.5, 10.0 mm/sec
Z Range:	335-620mm

Input: Wide variety of focal lengths with optional objectives

9" x 9" black and white or color

Output: 40" x 40" up to 4X magnification

Can plot drop-line contours

Capacity: Model scale to orthoscale 2:1 or 1:1

Double model capability off-line

Single model capability on-line

Slope Correction: Electronic interpolation of additional profiles: 1, 1/2, 1/3, 1/6 and fiberoptic interplation ring.

Remarks: Profiles are stored on storage plates and can be edited with ink.

SYSTEM:

ZEISS Ortho 3 Projector

Operation:

On-Line 3 projector

Scan:	Y direction, slit sizes 1X1, 2, 3, 4mm
Speeds:	1, 7, 3.3, 5.2, 10mm/sec
Z Range:	260 → 460mm

Input: 9" x 9" 153 ± 2.5mm focal length B+W

Output: 2.5 x magnification ± .5X

2.0 x ± .4 optional

Capacity: Single model

Slope Correction: None

Remarks: Elevation readout, model formed with anaglyphic illumination.

SYSTEM:

TBR Associates, Traster 77 (MATRA)

Operation Mode:

On-Line or Off-Line

Scan: Resolves .5 μ, speeds up to 25 mm/sec.

Input: 10" x 10" any focal length

Output: 1.1m x 1.4 m magnification 9-25X

Capacity: Not Available

Slope Correction: Two point linear interpolation

Remarks: Computer:

                             32 K words at 16 bits

                             750   sec cycle time

                             alphanumeric display 24 lines, 80 columns

                             universal input output coupler (32 inputs, 32 outputs and
                             service signals)

                         Optional:

                             Disk, cabled floating head, floppy disk, mag tape transport,
                             tape punch and reader.

SYSTEM:

SFOM 693 table (MATRA)

Operation:

On-Line

Scan: X scanning, slit lengths 5, 10, 20, 40mm x 2mm

                 Z range 150mm

Input: May equip a projection double beam plotters
                 Black and white and color

Output: 20.5" x 32.7"

                 magnification 2.5-4X

Capacity: 3 models , single model at a time
                   day

Scope Correction: None

Remarks: White light exposing with anaglyphic viewing

                 Can be hooked up to plotter table

                 Avg. quadratic error from 60,000 checks is less than
                 .15 mm for absolute position of a point relative to a grid.
                 Point to point is better.   Cost 17K.

SYSTEM:

9300 (MATRA)

Operation Mode:

On-Line

Scan: Scanning speed adjusted by intensity of projectors.

Input: 9" x 9" – B+W+color variable focal lengths

Output: Exposure control by scanning speed.

Magnification of 2.5-4X

Capacity: Not Available

Slope Correction: Not Available

Remarks: Not Available

SYSTEM:

Wild Avioplan OR1

Operation Mode:

On or Off-Line

Scan:	Slit sizes: 5, 8, 12, 16mm x .1 mm (B+W)
	x .3 mm (color)
	Optional: 3, 4, 6, 7, 9, 10, 11, 13, 14, 15mm
	Speeds up to 30mm/sec
Input:	Any focal length
	9" x 9" glass or film - Black and White or Color
	Digital object data in the form of image coordinates are produced by the wild B8
Output:	900mm x 750mm
	Magnification of .27→15X - Daylight operation, exposure controls with step wedge
	Can produce mirror reduced map images.
Capacity:	Not Available
Scope Correction:	Not Available
Remarks:	24 volt/150 watt/amp

Computer:

    8K 16 bit word length

    9 track 800 bp. i. NRZ1 tape unit

    Data codes pure binary, ASCII, EBCDIC

SYSTEM:

Wild PPO-8

Operation Mode:

On-Line with wild A-8 autograph

Scan: Parralelogram shaped slit

        Y direction scanning

        Slit lengths 2-12mm in 1mm steps

        Std. slits - 2, 3, 5, 8mm x .2mm (B+W)

                 x.6mm (color)

        Speeds: .8 - 12mm/sec - continuously adjustable while scanning

        Z Range: 175-350mm

Input: 9" x 9" Black and White or Color

        Focal lengths 98-215mm

Output: Magnification of .25:1 → 4:1 from model to orthophoto

        Magnification Range: .75 X → 6.15X

        Gray wedge exposure control, 500x 780mm output size

Capacity: $\dfrac{1 - 2 \text{ hours}}{\text{model}}$ single model

Slope Correction: None

Remarks: 50 watt halogen lamp

SYSTEM:

Galileo Orthophoto-Simplex

Operation Mode:

On-Line with stereosimplex IIC

Scan: Y direction slit sizes: 2.7, 4.0, 6.66mm

Speeds : 2.48, 3.34, 4.38 mm/sec

Z Range: 250mm

Input: 23 x 23mm focal lengths 85-220mm

Black and White or Color

Output: 23.6" x 11.8" magnification of 1.1-4.5X

digital terrain record is produced

Capacity: Single model $\dfrac{2.5 \text{ hrs}}{\text{model}}$

Slope Correction: None

Remarks: Permits film distortion correction

Cost $64K

SYSTEM:

Kelsh K-320

Operation Mode:

On or Off-Line

Scan: Y direction slit sizes 5, 10, 15, 20, 24mm x 1 to 1.5mm

                          adjustable X stepover in .025mm increments

             Speeds: 4, 8, 12, 16, 20, 24 mm/sec

             Z Range: 250mm

             Joystick control

             Rectangular or parallelogram slits

Input: Color or Black and White 9" x 9" 152 mm focal length will

             accept 88, 210, 305mm focal length photography if fairly level.

             Magnification: 3.8→5.8X

Output: 1100mm x 1100mm

             Image is transferred via fiber optics to film.

Capacity: $\dfrac{\text{2 dbl models}}{\text{shift}}$ Double model capacity

Slope Correction: Terrain data can be interpolated off-line

Remarks: Profile data is digitized.

             Fiber optics probe is on air bearings.

             Film bed is stationary and shutter platen moves.

             Depth of field focus.

             Cost $40K.

SYSTEM:

USGS Automatic orthophoto system

Operation Mode:

Off-line with analog profiler, autoline, and orthophotomat

Scan: Y direction, variable stepover

Z range: 4 inches with autoline (profile follower)
scan speed = 4-8mm/sec.

Input: 9" x 9" glass or film

Z range of orthophotomat = 6 inches.

Output: Magnification 2.8X - 27" x 27" vacuum surface

Flat to .001"

Exposing slits 1-3mm

Scan speed: $\dfrac{8\text{-}16mm}{sec}$

Capacity: 45 min. for double model.

Slope Correction: None

Remarks: Auto profiler: Ray intersection by stereo formation of edge

enhanced pos. and neg., capability of producing 7 profiles in

10 - 15 sec. two model capacity with baffle in middle. Profiles

are at model scale.

SYSTEM:

OMI AP/C-4 + OP/C-2

Operation Mode:

Off-Line

Scan: Slit lengths 2, 4, 8mm

                          Speeds: 20, 10, 5mm/sec

Input: 9" x 9"

Output: 9" x 9"

Capacity: Single model

Slope Correction: Not Available

Remarks: Computer:

                          CPU 8-bit   processor

                          Memory 2K by ROM + 768 by RAM paper tape input

                          8 channel ASCII coded.

APPENDIX B

SPOT SHAPING FOR RASTER SCANNED IMAGERY

SPOT SHAPING FOR RASTER SCANNED IMAGERY

Raster in scanned imagery can be suppressed to improve visual observation of image detail. This can be performed by optimal choice of scanning spot in the production of the rectified image. The optimal spot can be defined for scenes with a specific power spectrum. For scenes with $1/f^2$ power spectrum, the optimal spot is of diamond shape and extends over two scan lines.

This section addresses some analytical considerations in the derivation of an optimal spot shape for a raster scanned image production system. Such a scanning system can use light emitting diode or diode array with either diode masks or projection optics controlled to produce the ideal writing spot shape. This section describes means to implement spot shaping and gives an example of a raster and raster smoothed image to illustrate the process.

B. 1 Problem Statement

Consider a one-dimensional scene which varies only in the y direction, perpendicular to the direction of the scan. The resulting series of light and dark, horizontal bands has representation $s_o(y)$. It is sampled at intervals of Δy corresponding to the spacing of the raster lines. Then the sampled signal is displayed by spreading each sample in the y direction. Mathematically we have

$$s_1(y) = s_o(y) \, p(y) \quad * \quad h_1(y), \tag{B. 1}$$

where $s_1(y)$ is the signal that appears on the viewing screen, $p(y)$ is a sequence of equi-spaced impulses (the sampling function), $h_1(y)$ is the intensity profile of the writing spot, and "*" denotes spatial convolution over y .

If $s_1(y)$ is viewed through an optical viewing system with (incoherent) line spread function $h_2(y)$, (see Figure B. 1), the viewed scene is

$$s_2(y) = s_1(y) * h_2(y) . \tag{B. 2}$$

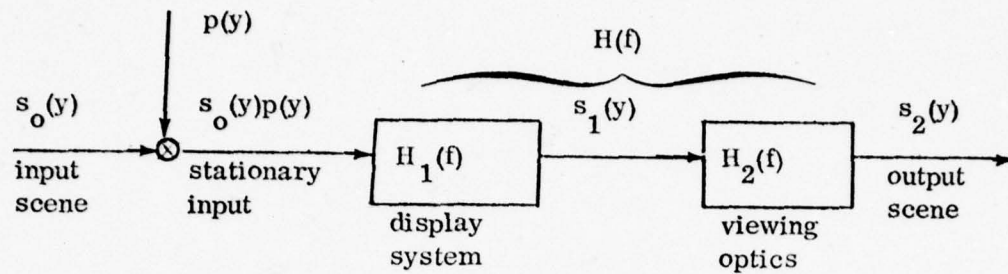Figure B.1 Linear Optical System

Thus from input to output $s_2(y)$ is

$$s_2(y) = s_o(y)\,p(y) \quad * \quad h(y) \tag{B.3}$$

where $h(y)$, the system line spread function, is

$$h(y) = h_1(y) * h_2(y). \tag{B.4}$$

The problem is to specify $h(y)$ (or $h_2(y)$ for a given $h_1(y)$) by minimization of the mean square error between $s_o(y)$ and $s_2(y)$.

B.2 Specification of h(y)

We assume that the input scene $s_o(y)$ is a realization of a stationary random process with known power spectrum $\Phi_o(y)$. We further assume that the sampling function $p(y)$ has a randomized starting position, independent of $s(y)$, such that $p(y)$ is also a stationary process with an auto-correlation function that is a sequence of impulses identical to $p(y)$. Thus the product $s_o(y)\,p(y)$ is also stationary.

If $s_2(y)$ must be a minimum mean square error estimator for $s_o(y)$, the optimal filter $H_2(f)$ is the Wiener filter with specification

$$H_2(f) = \frac{\Phi_{10}(f)}{\Phi_{11}(f)} \quad . \tag{B.5}$$

In (B.5) $\Phi_{11}(f)$ is the power spectrum of the input to $H_2(f)$, namely $s_1(y)$, and $\Phi_{10}(f)$ is the cross power spectrum between the input $s_1(y)$ and the desired output $s_0(y)$.

From linear system theory we can show that

$$\Phi_{10}(f) = H_1^*(f) \, \Phi_0(f) \tag{B.6}$$

and

$$\Phi_{11}(f) = |H_1(f)|^2 \sum_{k=-\infty}^{\infty} \Phi_0(f-k) \quad , \tag{B.7}$$

where we now assume that the sampling interval is $\Delta y = 1$. The second factor in (B.7) is the familiar aliased power spectrum of a sampled signal. The resulting $H_2(f)$ is

$$H_2(f) = \frac{1}{H_1(f)} \, \frac{\Phi_0(f)}{\sum \Phi_0(f-k)} \quad , \tag{B.8}$$

and $h_2(y)$ is the inverse Fourier transform of (B.8). The combined filter $H(f)$,

$$H(f) = H_1(f)H_2(f) \tag{B.9}$$

should be

$$H(f) = \frac{\Phi_0(f)}{\sum \Phi_0(f-k)} \quad . \tag{B.10}$$

We note that if additive noise, independent of $s_0(y)$, occurs at any point in the system, then (B.10) will become

$$H(f) = \frac{\Phi_0(f)}{\Phi_n(f) + \sum_0 (f-k)} \qquad (B.11)$$

where $\Phi_n(f)$ is the noise power spectrum seen at the input to $H_1(f)$.

B.3 Selection of Raster Spot Shape

There is evidence [1,2] that many scenes have a power spectrum of the form

$$\Phi_0(f) = \frac{a_0}{(f)^2 + \left(f_0\right)^2} \; , \qquad (B.12)$$

where a_0 is proportional to the scene's average intensity and f_0 is a "half power" frequency. For such a spectrum we can sum [3] the denominator of B.11 to get

$$H(f) = \left(\frac{1}{f^2 + f_0^2}\right)\left(\frac{f_0}{\pi}\right)\left(\frac{\cosh 2\pi f_0 - \cos 2\pi f}{\sinh 2\pi f_0}\right) \qquad (B.13)$$

The inverse transform is, after some algebraic manipulations,

$$h(y) = \begin{cases} \dfrac{\sinh 2f_0(1-y)}{\sinh 2 f_0} \; , & |y| < 1 \\[3mm] 0 \; , & |y| > 1 \; . \end{cases} \qquad (B.14)$$

This is the overall system line spread function required to optimally estimate $s_0(y)$ from $s_0(y)p(y)$. $h(y)$ is the "shape" of the optimal scanning spot.

In Figure B.2 we plot $h(y)$ for several values of f_0. Note that in all cases $h(y)$ vanishes for $|y| > 1$. Thus the optimal $h(y)$ has a profile peaking on the line scan of interest and vanishing exactly one

1. Huang, T.S., "The Subjective Effect of Two-Dimensional Pictorial Noise," IEEE Trans. IT, 11, 43 (1965).
2. Habibi, A. and Wintz, P.A., "Image Coding by Linear Transformation and Block Coding," IEEE Trans. CT, 19, 50 (1971).
3. Jolley, L., Summation of Series, Dover (1961) #858.
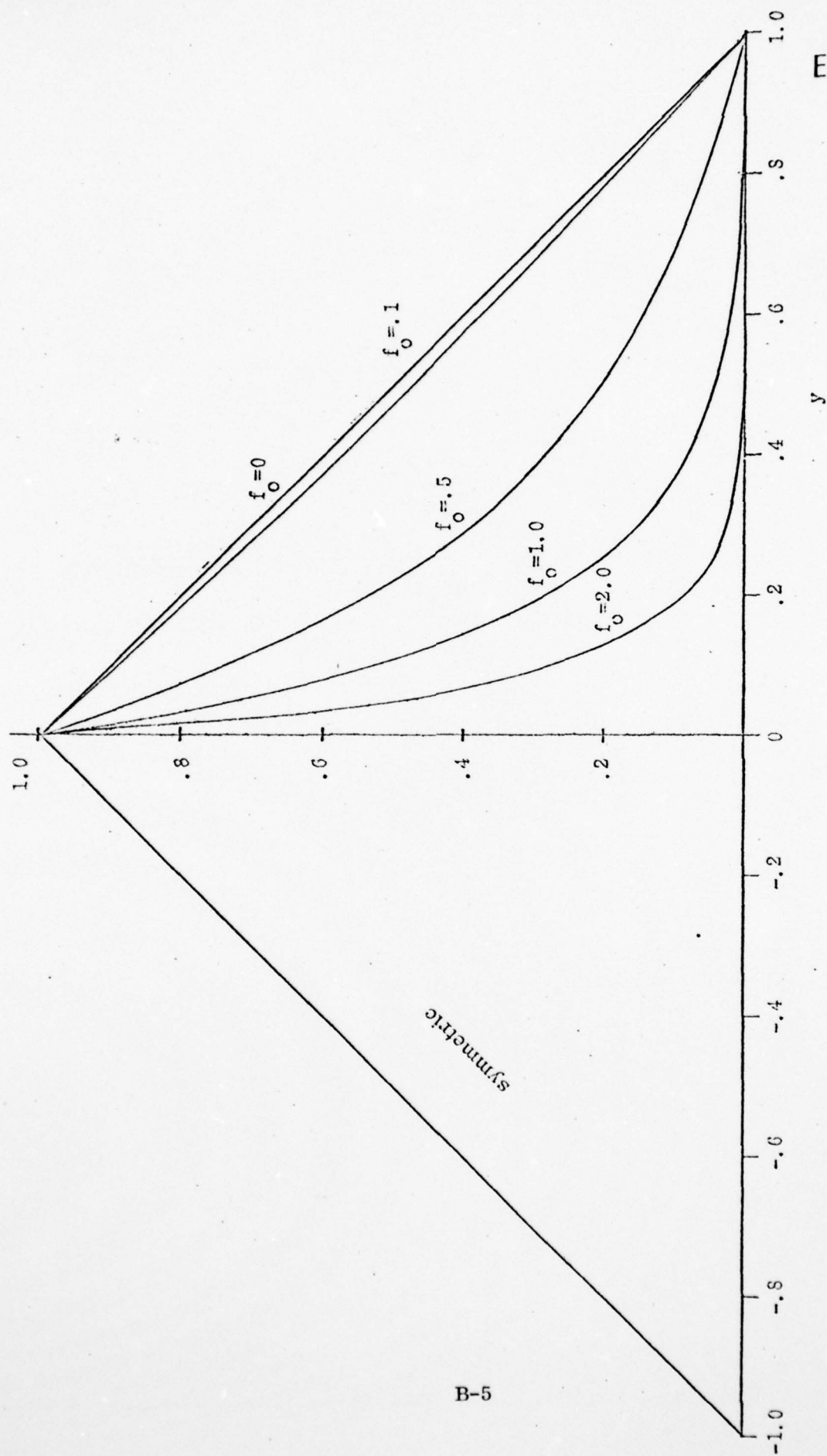
Figure B.2   Optimal $h(y)$ for $\Phi_o(f) = \dfrac{a_o}{(f)^2 + (f_o)^2}$

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line above and below. For f_0 approaching zero the profile becomes a triangle.

Finally we comment that if the two-dimensional profile $h(x, y)$ is a binary function (as with an LED), then $h(y)$ can be realized by letting the $|x|$ boundary be $h(y)$. For example, the triangle $h(y)$ can be realized with a diamond shaped LED (See Figure B.3).
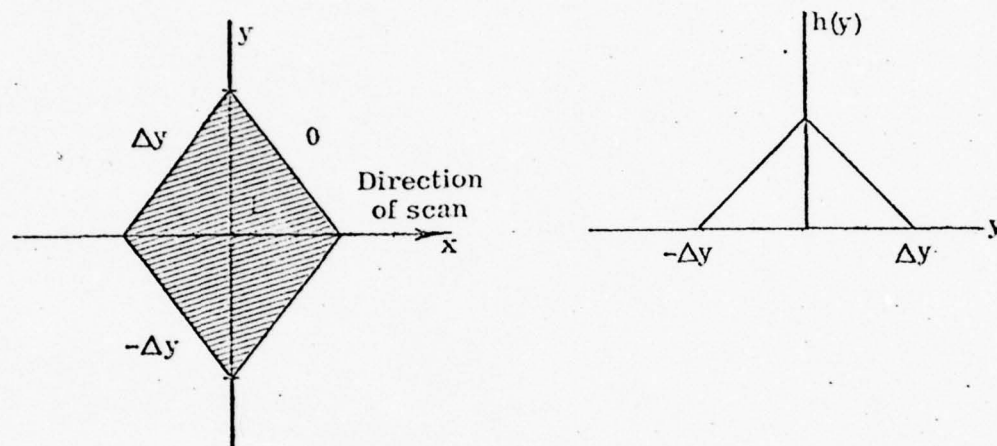

Figure B.3. $h(x, y)$ to Achieve the Optimal $h(y)$ for $\Phi_0 = \dfrac{1}{(f)^2}$.

B.4   Spot Shape for a Two-Dimensional Scene

If the input scene is $s_o(k, y)$, the output scene is

$$s_2(x, y) = s_o(x, y) \, p(y) \ast \ast \, h(x, y) \tag{B.15}$$

where $h(x, y)$ is the system point spread function (PSF). The optimal PSF has Fourier transform

$$H(f_x, f_y) = \frac{\Phi_0(f_x, f_y)}{\sum\limits_k \Phi_0\left(f_x, f_y - k\right)} \quad , \tag{B.16}$$

as we can easily show.

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For an input scene with spectrum

$$\Phi_0(f_x, f_y) = \frac{a_0}{\left(f_x\right)^2 + \left(f_y\right)^2} \tag{B.17}$$

The denominator sums as in (B.13) with f replaced by f_y and f_0 replaced by f_x. Then

$$h(x, y) = 2 \int_0^{\infty} h(y) \cos 2\pi x f_0 df_0 , \tag{B.18}$$

where $h(y)$ is given by B.14. This integral is tabulated.[4] The result is

$$h(x, y) = \begin{cases} \dfrac{1}{2} \dfrac{\sin \pi y}{\cos h\pi x - \cos \pi y} , & |y| < 1 \\ \\ 0 & , \quad |y| > 1 . \end{cases} \tag{B.19}$$

As before, $h(x, y)$ vanishes for $|y| > 1$. We note that the integral of (B.19) over the x-direction is the triangle function

$$\int_{-\infty}^{\infty} h(x, y)dx = \begin{cases} 1 - |y| , & |y| < 1 \\ \\ 0 & , \quad |y| > 1 . \end{cases} \tag{B.20}$$

That is, the line spread function for x-direction scanning reduces to the result derived earlier for a one-dimensional scene (as f_0 approaches zero).

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4. Bateman, H., Tables of Integral Transforms, McGraw Hill (1954), p. 31, # 14.

B. 5 Raster Scanned Imagery

The impact of spot shape and size is clearly evident in the output product of an image scanner. An image from a laser beam recorder is presented here that compares a scanned output having poor image quality with a smoothed output having improved image quality (Figure B. 4).
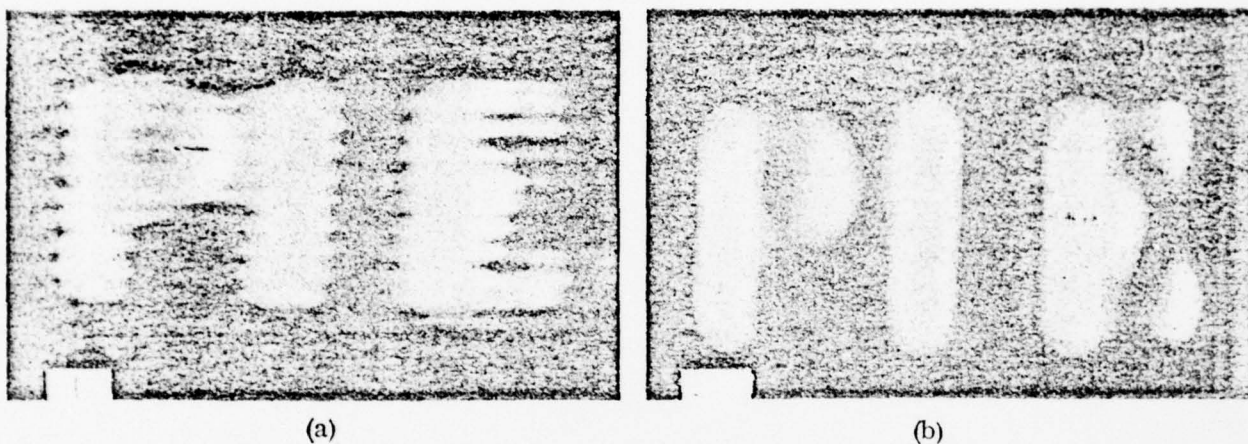

(a)   (b)

Figure B. 4   TV Rastered Image (a) and Filtered Image (b), Obtained by Incoherent Optical Filtering with a Phase-Only Filter